HEATING, COOLING, LIGHTING

SUSTAINABLE METHODS FOR ARCHITECTS

NORBERT LECHNER

FOURTH 4 EDITION



WILEY

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Sustainable Design Methods for Architects

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FOREWORD TO THE FOURTH EDITION

The compelling words written by James Marston Fitch in 1991 in the Foreword to the first edition (which follows) are still valid, but the stakes are now much higher. Because the fate of the planet is at stake, it is no longer just a question of following a particular architectural or design philosophy. Buildings consume about half the energy produced in the United States and around the world. Today, more than 50 percent of the world's population lives in cities, a figure that is likely to rise to 60 percent over the next two decades. It is clear that timing is critical: with 900 billion ft^2 (80 billion m^2) of urban environment projected to be built and rebuilt in the next twenty years (an area equal to three times the total building stock of the United States), we are presented with an extraordinary window of opportunity to meet present and looming threats. Our best chance of doing so is to ensure that the architecture, planning, and development community, the primary agents shaping the built environment through design and construction, have access to the knowledge and tools necessary for the transition to a decarbonized, sustainable, and adaptive world.

Professor Lechner's book describes how to achieve this transition in the built environment. The book illustrates the many sustainable strategies available to designers and provides the information needed during the early phases of the design process, when a building's energy consumption patterns are defined. By using the strategies presented in this book, much of the energy consumed to heat, light, and cool buildings can be dramatically reduced.

Professor Lechner's book is also an important resource for those architects who are concerned about the aesthetic aspects of sustainability. He convincingly explains and demonstrates how lessons learned from vernacular architecture can be combined with the best of modern ideas to create low-impact yet beautifully designed humane architecture. Since carbon neutral buildings can be fully powered by renewable resources, a future of low-impact buildings is not only necessary but also elegantly achievable.

EDWARD MAZRIA, AIA

FOREWORD TO THE FIRST EDITION

Professor Lechner's book differs from most of its predecessors in several important respects: (1) he deals with the heating, cooling, and lighting of buildings, not as discrete and isolated problems, but in the holistic sense of being integral parts of the larger task of environmental manipulation; (2) he deals with the subjects not merely from the engineer's limited commitment to mechanical and economic efficiency but from the much broader viewpoint of human comfort and physical and psychic well being; (3) he deals with these problems in relation to the central paradox of architecture—how to provide a stable, predetermined internal environment in an external environment that is in constant flux across time and space; and finally, (4) he approaches all aspects of this complex subject from a truly cultural—as opposed to a narrowly technological—perspective.

This attitude toward contemporary technology is by no means hostile. On the contrary, Professor Lechner handles it competently and comprehensively. But he never loses sight of the fact that the task of providing a truly satisfactory enclosure for human activity is that one must view the building as a whole. He points out, quite correctly, that until the last century or so, the manipulation of environmental factors was, of necessity, an architectural problem. It was the building itself—and only incidentally any meager mechanical equipment that the period happened to afford—that provided habitable space. To illustrate this point, he makes continuous and illuminating analysis to both high-style and vernacular traditions, to show how sagaciously the problems of climate control were tackled by earlier, prescientific, premechanized societies.

This is no easy-to-read copybook for those designers seeking shortcuts to glitzy postmodern architecture. On the contrary, it is a closely reasoned, carefully constructed guide for architects (young and old) who are seeking an escape route from the energy-wasteful, socially destructive cul-de-sac into which the practices of the past several decades have led us. Nor is it a Luddite critique of modern technology; to the contrary, it is a wise and civilized explication of how we must employ technical and scientific knowledge if we in the architectural field are to do our bit toward avoiding environmental disaster.

JAMES MARSTON FITCH
Hon. AIA, Hon. FRIBA
In memory of James Marston Fitch, architect, historian, professor, preservationist, and architectural theorist, 1909–2000.

PREFACE

In this new edition the goal of previous editions remains: to provide the appropriate knowledge at the level of complexity needed at the schematic design stage. In the years since the first edition was published, we have moved from a shortage of information to a flood because of the Internet. This book will aid the designer because it presents the information in a concise, logical, and accessible arrangement and at a useful level.

Since heating, cooling, and lighting are accomplished by adding energy to or removing it from a building, and since the consumption of energy is causing global warming, it is vital for architects to design low energy, sustainable buildings. Although sustainability deals with many issues, the energy issues are the most critical. Thus, an additional goal of this book is to provide architects with the skills and knowledge needed to create low energy and low carbon-emission buildings.

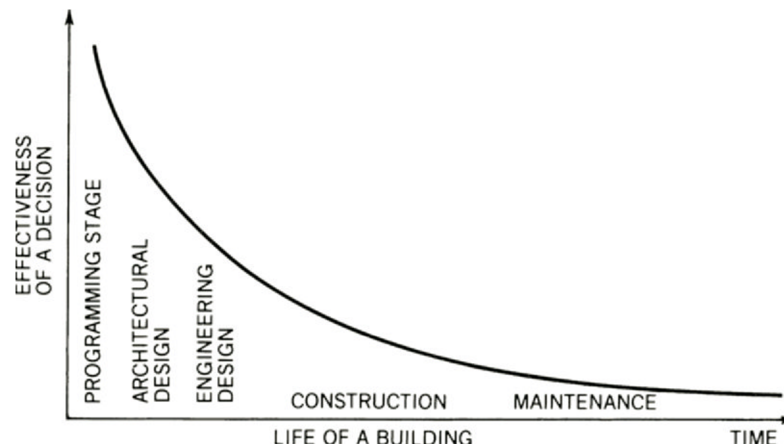
In addition to improving and updating every chapter, three new chapters have been added. Chapter 17 on tropical architecture was added because a large portion of the world's population lives in the tropical zone and because many architects trained in designing buildings in temperate climates end up designing buildings in the tropics. Case studies, formerly in Chapter 17, are now in Chapter 18. Because of the extensive information available on the Web, only a brief description is given of a personal selection of buildings.

Chapter 19, the third new chapter, presents a checklist to help in the design of low energy, sustainable buildings. The checklist guides the designer through the decision-making process so that important options are considered at the appropriate time.

This book focuses on the schematic design stage, where the key decisions are made. The graph below points out how the earliest decisions have the greatest impact on a project. A building's cost and environmental impact are established mainly at the schematic design stage. The most basic decisions of size, orientation, and form often have the greatest impact on the resources required during both construction and operation. Thus, designs for sustainable buildings are achieved primarily by the earliest decisions in the design process rather than by add-ons and engineering decisions made after the architectural design of the building has been essentially completed.

The information in this book is presented to support the three-tier approach to sustainable design of the heating, cooling, and lighting of buildings. The first tier is load avoidance. Here the need for heating, cooling, and lighting is minimized by the design of the building itself. The second tier consists of using natural energies through methods such as passive solar, passive cooling, natural ventilation, and daylighting. This tier is also accomplished mainly by the design of the building itself. The third and last tier uses mechanical and electrical equipment to satisfy the needs not provided for by the first two tiers.

With the knowledge and information presented in this book, the first two tiers can provide most of the thermal and lighting requirements of a building. As a consequence, the mechanical and electrical equipment of the third tier will be substantially smaller and will use much less energy than is typical now, thereby resulting in more sustainable buildings. Since tiers one and two are the domain of the architect, the role of the engineer at the third tier is to provide only the heating, cooling, and lighting that the architect could not.



ACKNOWLEDGMENTS

For the fourth edition, I would like to thank especially John Marusich for his excellent work on the new and revised drawings. Since this book is built on the previous three editions, I also want to thank again all of the people who helped me write those earlier editions. The typing and proofreading for the fourth edition were done by my son, Walden Lechner. And again, I want to thank my wife, Prof. Judith Lechner, whose help, support, and love are invaluable to me.

NORBERT LECHNER
Prof. Emeritus and Architect
Auburn University

CHAPTER



HEATING, COOLING, AND LIGHTING AS FORM-GIVERS IN ARCHITECTURE

Two essential qualities of architecture [commodity and delight], handed down from Vitruvius, can be attained more fully when they are seen as continuous, rather than separated, virtues.

. . . In general, however, this creative melding of qualities [commodity and delight] is most likely to occur when the architect is not preoccupied either with form-making or with problem-solving, but can view the experience of the building as an integrated whole. . . .

John Morris Dixon,
Editor of* Progressive Architecture*, 1990

All design projects should engage the environment in a way that dramatically reduces or eliminates the need for fossil fuel.

The 2010 Imperative,
Edward Mazria, AIA,
Founder of Architecture 2030

1.1 INTRODUCTION

Architecture has been called journalism in stone, since it reflects the culture, climate, and resources of the time and place. During the Renaissance, for example, the main influence was the rediscovery of the classical world. What is the agent of change today?

The story that is now shaping the future of architecture is sustainability. There are few people left today who are not in favor of creating a sustainable world or who would claim that we are living in a sustainable world. Since building impacts the environment more than any other human activity, architects have both the responsibility and the opportunity to lead humankind to a sustainable future.

Sustainable architecture can be achieved by using "the best of the old and the best of the new." A new architecture is being created by using modern science, technology, and ideas of aesthetics combined with traditional ideas that responded to human needs, regionalism, and climate. Such architecture will be more varied than contemporary architecture, which gives no clue to where a building is located. Much contemporary architecture looks the same in New York, Paris, New Delhi, or Tokyo. Furthermore, this de facto "international" architecture is equally inappropriate wherever it is built since it is not sustainable for any climate.

Sustainability covers many issues, but none is as important as energy consumption. More than any other factor, the energy consumption of buildings is destroying the planet as we know it. Buildings use about 48 percent of all the energy consumed, with 40 percent for their operation and 8 percent for their construction (Fig. 1.1a). This energy is mostly derived from fossil sources that produce the carbon dioxide that is the main cause of global warming. We must replace these polluting sources with clean, renewable energy sources such as wind, solar energy, and biomass, or we must increase the efficiency of our building stock so that it uses less energy. Of course, we need to do both, but decreasing the energy consumption of buildings is both quicker and less expensive. Furthermore, the design of energy-responsive buildings will yield a new aesthetic that can replace both the blandness of most modern buildings and the inappropriate copying of previous styles.

Is it really possible for architecture to seriously address the problem of global warming? The answer is an unambiguous yes, both because present buildings are so wasteful of energy and because we know how to design and construct buildings that use 80 percent less energy than the standard new building. Presently, there are architects around the world designing "zero-energy buildings," which are designed to use as little energy as possible, with the small remaining load being met mostly by on-site renewable energy such as photovoltaics (Fig. 1.1b). We have the know-how (see Sidebox 1.1); all we need is the will.

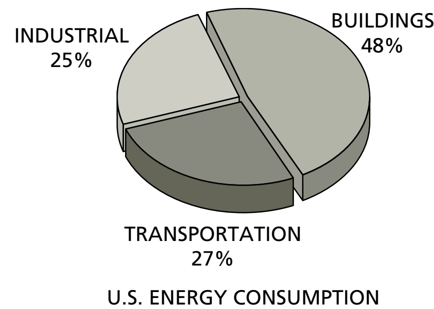


Figure 1.1a Buildings are the main cause of global warming because they use about 48 percent of all energy. Of that 48 percent, about 40 percent is for operating the buildings (heating, cooling, lighting, computers, etc.) and about 8 percent is for their construction (creating materials, transportation, and erection). (Courtesy of Architecture 2030.)

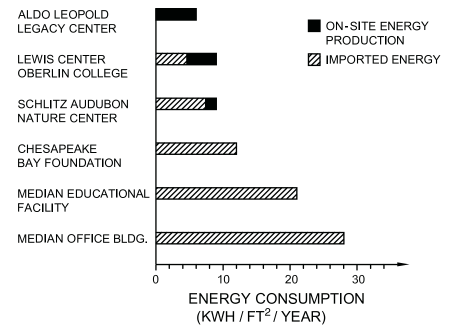


Figure 1.1b The good news is that buildings do not have to use climate-changing fossil fuels. Over the years, we have learned how to design buildings so energy efficient that we can now build zero-energy buildings. The small amount of energy that they still need can be supplied by renewable sources such as photovoltaics on the roof.

SIDEBOX 1.1

Characteristics of a Zero-Energy House

- Correct orientation
- Form as compact as appropriate for the climate and function
- Extensive use of white or very light colored surfaces
- Superinsulated walls, roof, and floor
- Airtight construction with a heat recovery unit for ventilation
- High-performance, properly oriented windows
- Windows fully shaded in summer
- Passive solar space heating
- Active solar domestic hot water
- High-efficiency appliances
- High-efficiency electric lighting
- High-efficiency heating and cooling equipment (e.g., earth-coupled heat pump)
- Photovoltaics on roof that produce the small amount of electricity still needed

There is a widespread belief that engineers design the heating, cooling, and lighting of buildings. The truth is that they only design the systems and equipment still needed after the architect designs the building to heat, cool, and light itself. Thus, the size of the mechanical and electrical equipment is an indicator of how successful the architect was. It is most important to realize that in designing a building to do most of the heating, cooling, and lighting, the architect is also designing the form and other aesthetics of a building.

This book was written to help the reader design sustainable buildings that use very little energy. It presents rules of thumb, guidelines, and examples that are drawn from the best of the old and the best of the new. Because traditional buildings used little energy, the methods they used to respond to their climate, locality, and culture can be a source of ideas and inspiration for modern architects.

1.2 INDIGENOUS AND VERNACULAR ARCHITECTURE

One of the main reasons for regional differences in architecture is the response to climate. This becomes apparent when looking at indigenous buildings, because they usually reflect the climate in which they were built.

In hot and dry climates, one usually finds massive walls and roofs used for their time-lag effect. Since the sun is very intense, small windows will adequately light the interiors. The windows are also small because during the daytime the hot outdoor air makes ventilation largely undesirable. The exterior surface colors are usually very light to minimize the absorption of solar radiation. Interior surfaces are also light to help diffuse the sunlight entering through the small windows (Fig. 1.2a).

Since there is usually little rain, roofs can be flat and are often used as additional living and sleeping areas during summer nights. Outdoor areas cool quickly after the sun sets because of the rapid radiation to the clear night sky. Thus, roofs are more comfortable than the interiors, which are still quite warm from the daytime heat stored in the massive construction.

Even community planning responds to climate. In hot and dry climates, buildings are often closely clustered for the shade they offer one another and the public spaces between them.

In hot and humid climates, we find a very different kind of building. Because water vapor blocks some solar radiation, air temperatures are lower than in hot and dry climates, but the high humidity still creates great discomfort. The main relief comes from shading and moving air across the skin to increase the rate of evaporative cooling. The typical antebellum house (see Fig. 1.2b) responds to the humid climate by its use of many large windows, large overhangs, shutters, light-colored walls, and high ceilings. The large windows maximize ventilation, while the overhangs and shutters protect from both solar radiation and rain. The light-colored walls minimize heat gain.

Since in humid climates nighttime temperatures are not much lower than daytime temperatures, massive construction is a disadvantage. Buildings are, therefore, usually made of lightweight wood construction. High ceilings permit larger windows and allow the air to stratify with people inhabiting the lower and cooler layers. Vertical ventilation through roof monitors or high windows not only increases ventilation but also exhausts the hottest air layers first. For this reason, high gabled roofs without ceilings (i.e., cathedral ceilings) are popular in many parts of the world that have hot and humid climates (Fig. 1.2c). Buildings are sited as far apart as possible for maximum access to the cooling breezes. In some humid regions of the Middle East, wind scoops are used to further increase the natural ventilation through the building (Fig. 1.2d).

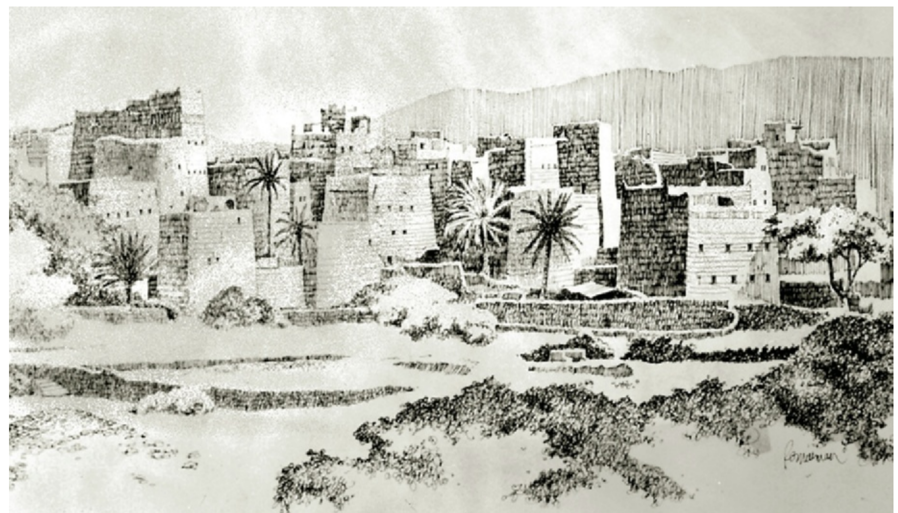


Figure 1.2a Massive construction, small windows, and light colors are typical in hot and dry climates, as in this Yemeni village. It is also common, in such climates, to find flat roofs and buildings huddled together for mutual shading. (Drawing by Richard Millman.)



Figure 1.2b In hot and humid climates, natural ventilation from shaded windows is the key to thermal comfort. This Charleston, South Carolina, house uses covered porches and balconies to shade both windows and walls, as well as to create cool outdoor living spaces. The white color and roof monitor are also important in minimizing summer overheating.

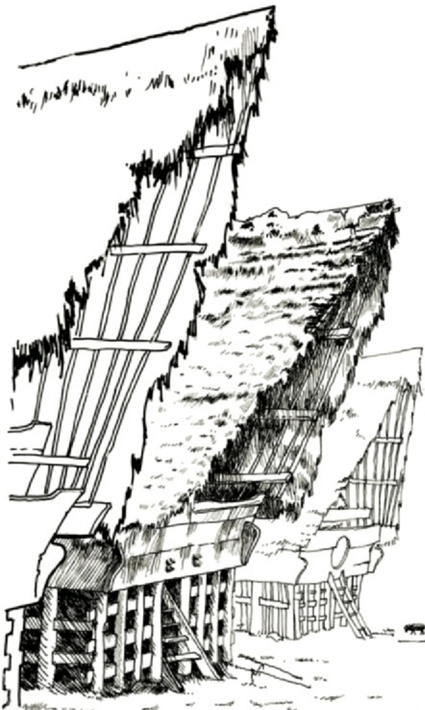


Figure 1.2c In hot and humid climates such as in Sumatra, Indonesia, native buildings are often raised on stilts and have high roofs with open gables to maximize natural ventilation.



Figure 1.2d When additional ventilation is desired, wind scoops can be used, as on this reconstructed historical dwelling in Dubai. Also note the open weave of the walls to further increase natural ventilation. Although this is a desert area, lightweight construction is appropriate because the region along the Persian Gulf is humid. (Photograph by Richard Millman.)



Figure 1.2e Bay windows are used to capture as much light as possible in a mild but very overcast climate such as that found in Eureka, California.



Figure 1.2f In cold climates, compactness, thick wooden walls, and a severe limit on window area were the traditional ways to stay warm. In very cold climates, the fireplace was located either on the inside of the exterior wall or in the center of the building. The log cabin was introduced to America by early Swedish settlers.

In mild but very overcast climates, like the Pacific Northwest, buildings open up to capture all the daylight possible. In this kind of climate, the use of bay windows is quite common (Fig. 1.2e).

In a predominantly cold climate, we again see a very different kind of architecture. In such a climate, the emphasis is on heat retention. Buildings, like the local animals, tend to be very compact to minimize the surface-area-to-volume ratio. Windows are few because they are weak points in the thermal envelope. Since the thermal resistance of the walls is very important, wood rather than stone is usually used (Fig. 1.2f). Because hot air rises, ceilings are kept very low—often below 7 ft (2.2 m). Trees and landforms are used to protect against the cold winter winds. In spite of the desire for views and daylight, windows are often sacrificed for the overpowering need to conserve heat.

Despite the name, temperate climates are not mild. Instead, they are usually cold in the winter and hot in the summer. Consequently, temperate climates are difficult to design for.

1.3 FORMAL ARCHITECTURE

Throughout history, most master builders and architects have included environmental controls in their designs, just as their unschooled neighbors creating indigenous buildings did. After all, the Greek portico is simply a feature to protect against the rain and sun (Fig. 1.3a). The perennial popularity of classical architecture is based on not only aesthetic but also practical grounds. There is hardly a better way to shade windows, walls, and porches than with large

overhangs supported by columns (Fig. 1.3b).

The Roman basilicas consisted of large high-ceilinged spaces that were very comfortable is hot climates during the summer. Clerestory windows were used to bring daylight into these central spaces. Both the trussed roof and groin-vaulted basilicas became prototypes for Christian churches (Fig. 1.3c).

One of the Gothic builders' main goals was to maximize the window area for a large, fire-resistant hall. By means of the inspired structural system of groin vaulting, they were able to



Figure 1.3a The classical portico has its functional roots in the sun- and rain-protected entrance of the early Greek megaron. Maison Carrée, Nîmes, France.



Figure 1.3b The classical revival style was especially popular in the South because it was suitable for hot climates.

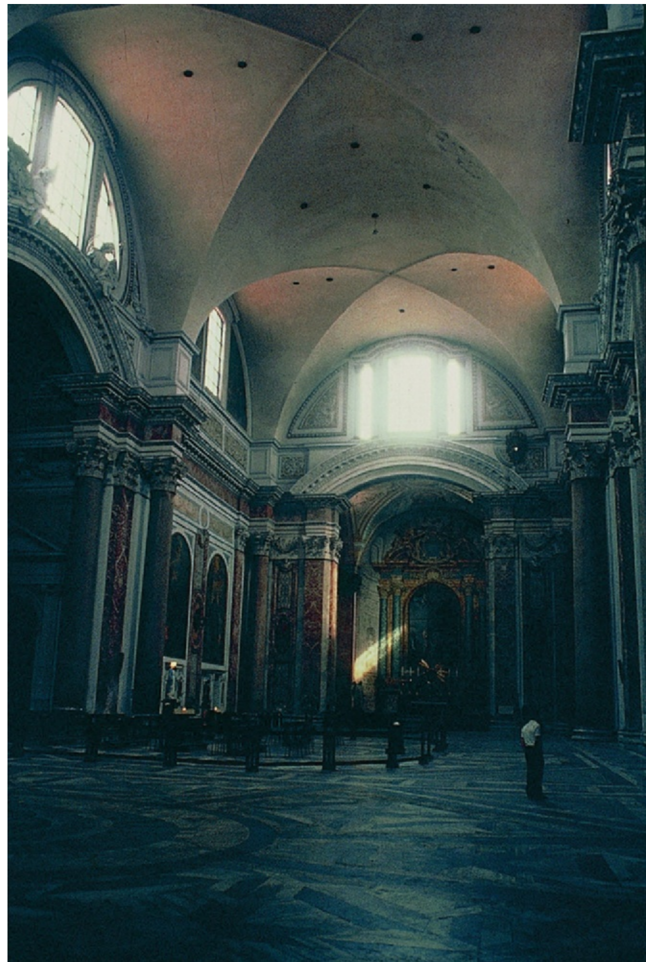


Figure 1.3c Roman basilicas and the Christian churches based on them used clerestory windows to light the large interior spaces. The Thermae of Diocletian, Rome (A.D. 302), was converted by Michelangelo into the church of Santa Maria degli Angeli. (Photograph by Clark Lundell.)

send an abundance of daylight through stained glass windows (Fig. 1.3d).

The need for heating, cooling, and lighting had also affected the work of the twentieth-century masters such as Frank Lloyd Wright. The Marin County Civic Center emphasizes the importance of shading and daylighting. To give most offices access to daylight, the building consists of linear elements separated by a glass-covered atrium (Fig. 1.3e). The outside windows are shaded from the direct sun by an arcade-like overhang (Fig. 1.3f). Since the arches are not structural, Wright shows them hanging from the building.

Modern architecture prided itself on its foundation of logic. "Form follows function" was seen as much more sensible than "form follows some arbitrary historical style." However, "function" was usually interpreted as referring to structure or building circulation. Rarely did it refer to low energy usage, which was seen as a minor issue at best and usually was not considered at all. Although that belief was never logical, it is clearly wrong today since energy consumption is the number-one issue facing the earth.

Like Frank Lloyd Wright, Le Corbusier also felt strongly that the building itself should be effective in heating, cooling, and lighting. He included thermal comfort and energy as functions in his interpretation of "form follows function." His development of the brise-soleil (sunshades) will be discussed in some detail later. A feature found in a number of his buildings is the parasol roof, an umbrella-like structure covering the whole building. A good example of this concept is the Maison de l'Homme, which Le Corbusier designed in glass and painted steel (Fig. 1.3g).

Today, with no predominant style guiding architects, they occasionally use a mild form of revivalism. The buildings in Figure 1.3h use the classical portico for shading. Such historical adaptations can be more climate responsive than the "international style," which typically ignores the local climate. Buildings in cold climates can continue to benefit from



Figure 1.3d Daylight gained a mystical quality as it passed through the large stained glass windows of the Gothic cathedral made possible by groin vaulting. (Photograph by Clark Lundell.)



Figure 1.3e In the linear central atrium of the Marin County Civic Center, Frank Lloyd Wright used white surfaces to reflect light down to the lower levels. The offices facing the atrium have all-glass walls.



Figure 1.3f The exterior windows of the Marin County Civic Center are protected from direct sun by an arcade-like exterior corridor.



Figure 1.3g The Maison de l'Homme in Zurich, Switzerland, demonstrates the concept of the parasol roof. The building is now called Centre Le Corbusier. (Photograph by William Gwin.)



Figure 1.3h These postmodern buildings promote the concept of regionalism in that they reflect a previous and appropriate style of the hot and humid Southeast.

compactness, and buildings in hot and dry climates still benefit from massive walls and light exterior surfaces. Looking to the past in one's locality helps lead to the development of new and sustainable regional styles.

1.4 THE ARCHITECTURAL APPROACH TO SUSTAINABLE DESIGN

The sustainable design of heating, cooling, and lighting buildings can be more easily accomplished by understanding the logic of the three-tier approach to sustainable design (Fig. 1.4a). The first tier consists of all of the decisions that are made in designing any building. When the designer consistently thinks of minimizing energy consumption as these decisions are made, the building itself can accomplish about 60 percent of the heating, cooling, and lighting.

The second tier involves the use of natural energies through such methods as passive heating, passive cooling, and daylighting systems. The proper decisions at this point can reduce the energy consumption another 20 percent or so. Thus, the strategies in tiers one and two, both purely architectural, can reduce the energy consumption of buildings up to 80 percent. Tier three consists of designing the mechanical and electrical equipment to be as efficient as possible. That effort can reduce energy consumption another 5 percent or so. Thus, only 15 percent as much energy is needed as in a conventional building. That small amount of energy can be derived from renewable sources both on- and off-site. Table 1.4A shows some of the design topics that are typical at each of the three tiers.

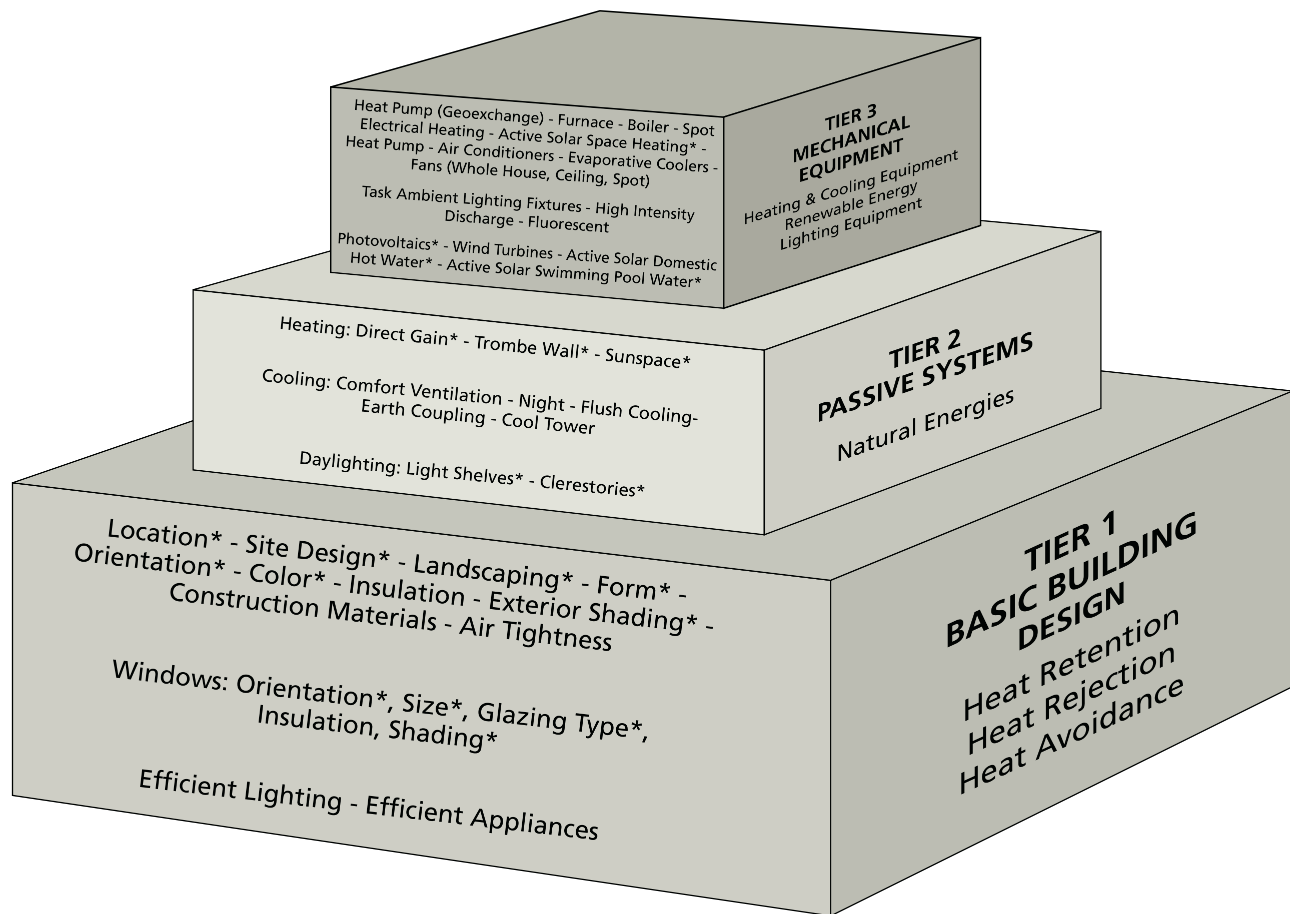


Figure 1.4a The three-tier approach to the sustainability design of heating, cooling, and lighting is shown. Tiers one and two are the domain of the architect, and proper design decisions at these two levels can reduce the energy consumption of buildings as much as 80 percent. All items with an asterisk are part of solar-responsive design. This image can be downloaded in color for free and used as a poster. It is available at www.heliodons.org.

Table 1.4A The Three-Tier Design Approach

	Heating	Cooling	Lighting
Tier 1	*Conservation*	*Heat avoidance*	*Daylight*
Basic Building Design	1. Surface-to-volume ratio 2. Insulation 3. Infiltration	1. Shading 2. Exterior colors 3. Insulation 4. Mass	1. Windows 2. Glazing type 3. Interior finishes
Tier 2	*Passive solar*	*Passive cooling*	*Daylighting*
Natural Energies and Passive Techniques	1. Direct gain 2. Trombe wall 3. Sunspace	1. Evaporative cooling 2. Night-flush cooling 3. Comfort ventilation 4. Cool towers	1. Skylights 2. Clerestories 3. Light shelves
Tier 3	*Heating equipment*	*Cooling equipment*	*Electric light*
Mechanical and Electrical Equipment	1. Furnace 2. Boiler 3. Ducts/Pipes 4. Fuels	1. Refrigeration machine 2. Ducts 3. Geo-exchange	1. Lamps 2. Fixtures 3. Location of fixtures

The heating, cooling, and lighting design of buildings always involves all three tiers, whether consciously considered or not. Unfortunately, in the recent past minimal demands were placed on the building itself to affect the indoor environment. It was assumed that it was primarily the engineers at the third tier who were responsible for the environmental control of the building. Thus, architects sometimes designed buildings that were at odds with their environment. For example, buildings with large glazed areas were designed for very hot or very cold climates. The engineers were then forced to design giant, energy-guzzling heating and cooling plants to maintain thermal comfort. Ironically, these mostly glass buildings had their electric lights on

during the day, when daylight was abundant, because they were not designed to gather quality daylighting. As this shows, a building's energy consumption for heating, cooling, and lighting is mainly determined by the architect at the conceptual design stage.

In some climates, it is possible to reduce the mechanical equipment to zero. For example, Amory Lovins designed his home/office for the Rocky Mountain Institute in Snowmass, Colorado, where it is very cold in the winter and quite hot in the summer, to have no heating or cooling system at all. He used the strategies of tiers one and two to accomplish most of the heating and cooling, and he used photovoltaics, active solar, and very occasionally a wood-burning stove for any energy still needed.

Table 1.4B Building Form Implications

	Advantages	Disadvantages
I.	• compactness to minimize surface area, thereby reducing heat gain/loss • minimum footprint on land • good for cold climates	• cannot be oriented to give most windows the ideal orientation of north and south • minimum potential for daylighting, passive solar, and passive cooling
II.	• better for daylighting and natural ventilation than form I • more people have access to views, although some only to the atrium	• cannot be oriented to give most windows the ideal orientation of north and south • less compact than form I unless atrium is covered • larger footprint on land than form I
III.	• daylighting for whole space if one story and daylighting for most if two stories • very high quality daylighting since it is mostly top lighting • very high potential for passive solar heating through south-facing clerestories • high potential for passive cooling through: • roof vents for natural and forced ventilation • solar chimneys • direct evaporative cooling from roof • no vertical circulation needed if one story and little vertical circulation if two stories	• very large footprint on land • very large surface-area-to-volume ratio • all windows cannot face the ideal orientation of north and south, but clerestories can
IV.	• if site permits, all or most windows can face the ideal orientation of north and south • very high potential for daylighting • high potential for cross ventilation • very high potential for passive solar heating	• larger surface to volume ratio than either form I or II • if the site requires the long facades to face east and west, the building will perform poorly; cooling loads will be very high due to all or most windows facing east or west; quality daylighting will also be poor
V.	• can fit on sites that may not work for form IV • good potential for daylighting especially for the windows facing north and south • very good potential for cross ventilation	• only some windows can face the ideal orientation of north and south • many windows will be facing the problematic orientations of east and west

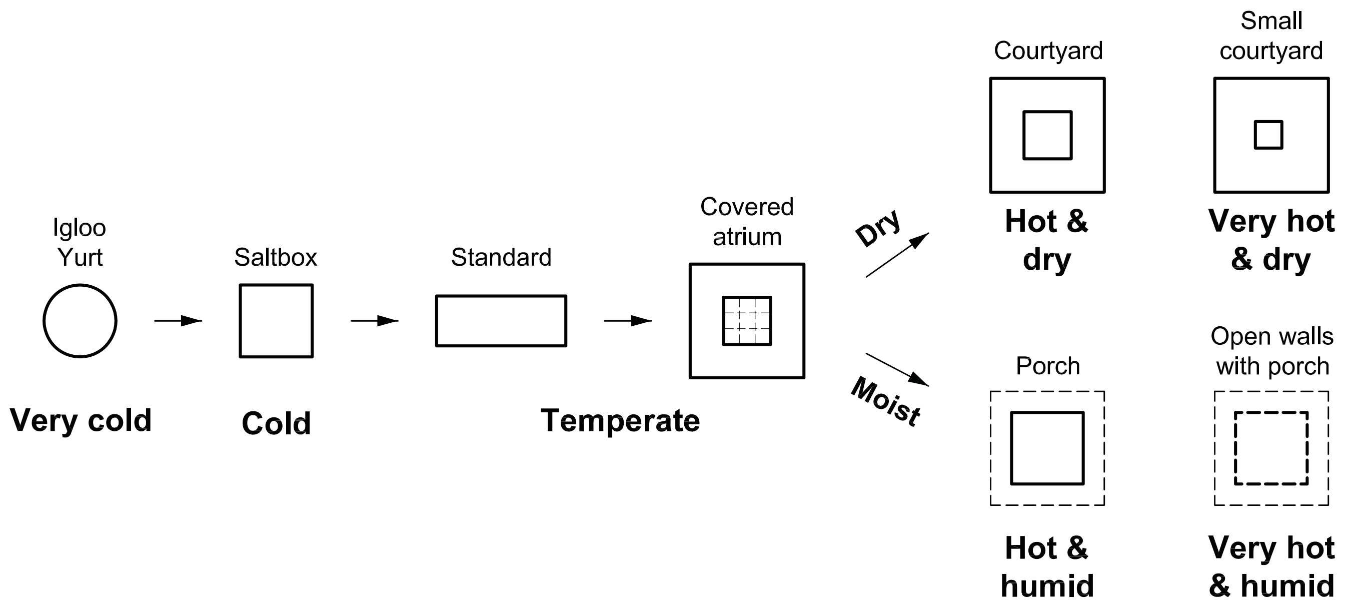


Figure 1.4b The ideal building form is greatly influenced by the local climate. The building form can minimize heat loss or gain, affect maximum daylighting, and maximize natural ventilation.

When it is consciously recognized that each of these tiers is an integral part of the heating, cooling, and lighting design process, buildings are improved in several ways: they can be less expensive because of reduced mechanical equipment and energy needs; they are usually also more comfortable because the mechanical equipment does not have to fight such giant thermal loads; and they are often more interesting because some of the money that is normally spent on the mechanical equipment is spent instead on the architectural elements. Unlike hidden mechanical equipment, features such as shading devices are a very visible part of the exterior aesthetic—thus, the name of this chapter is "Heating, Cooling, and Lighting as Form-Givers in Architecture."

Table 1.4B outlines the advantages and disadvantages of the main massing schemes. Figure 1.4b illustrates how massing relates to climate in traditional building. The appearance of a building is also impacted by surface treatments such as shading devices, balconies, and green walls, which further impact the heating, cooling, and lighting of a building.

1.5 DYNAMIC VERSUS STATIC BUILDINGS

Is it logical that a static system can respond to a dynamic problem? A building experiences a very dynamic environment: cold in the winter, hot in the summer, sunny one day, cloudy the next, sunshine from the east in the morning and west in the afternoon, and the angle of sunrays changing minute by minute and day by day. Nevertheless, most buildings are static except for the mechanical and electrical equipment. Would it not make more sense for the building itself to change in response to the environment? The change can occur continuously over a day as, for example, a movable shading device that extends when it is sunny and retracts when it is cloudy. Alternatively, the change could be on an annual basis, whereby a shading device is extended for the summer and retracted for the winter, much like a deciduous tree. The dynamic aspect can be modest, as in movable shading devices, or it can be dramatic, as when the whole building rotates to track the sun (Figs. 9.15b to 9.15d). Since dynamic buildings are more energy efficient than static ones, it is likely that all future buildings will have dynamic facades. A major objection has been the difficulty of maintaining movable systems exposed to the weather. However, the present reliability of cars shows that movable systems can be made that need few if any repairs over long periods of time. With good design and materials, exposed building systems have become extremely reliable even with exposure to salt water and ice in the winter. Perhaps the modern airplane is an even better example of a reliable movable system than the automobile. Since no one shape of wing is ideal for all stages of flight, modern passenger jets change the shape of their wings as conditions change (Fig. 1.5). If planes can do this flying at hundreds of miles per hour in all weather conditions, certainly a building on the ground moving zero miles per hour can also have extremely reliable dynamic facades.

Not only will dynamic buildings perform much better than static buildings, but they will also provide an exciting aesthetic, the aesthetic of change. Numerous examples of dynamic buildings are included throughout the book, but most will be found in the chapters on shading, passive cooling, and daylighting.

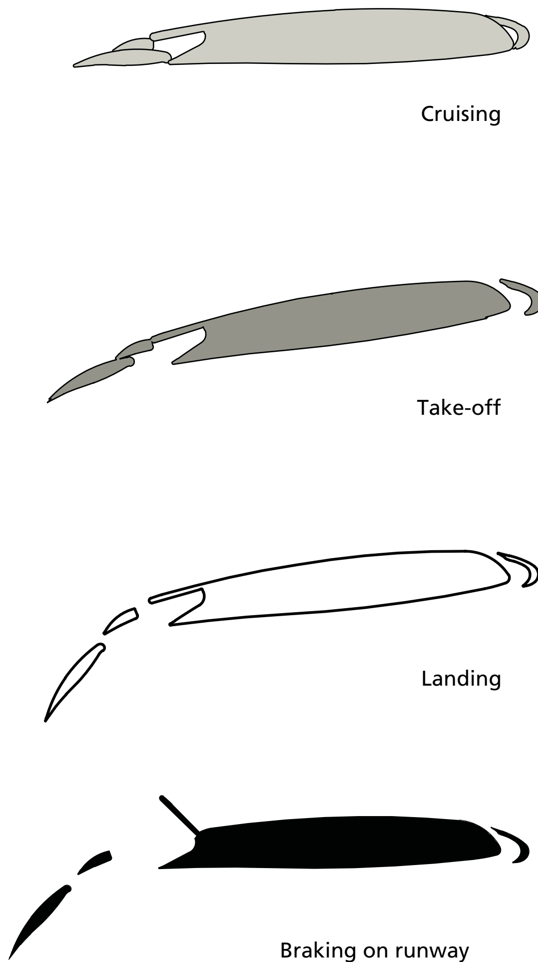


Figure 1.5 Dynamic building facades are often rejected in the belief that exposed movable systems are doomed to fail. The changing shape of the wings on a jet airliner indicates that movable exterior systems can be completely reliable even with snow, ice, rain, and winds of several hundred miles per hour.

1.6 RESILIENT DESIGN

We should design buildings not only to sustain the planet but also to sustain its occupants during an emergency. For example, houses on stilts had a better chance to survive the storm surges of Hurricanes Katrina and Sandy than the typical houses built close to the ground.

We rely on our buildings' mechanical systems and imported energy supplies to keep us warm in the winter, cool in the summer, and out of the dark all year. Yet, in January 1998, an ice storm in eastern Canada left four million people without power for weeks during the height of the winter. Heat waves in the United States and Europe are becoming more severe and frequent. Is it wise to rely on mechanical equipment and uninterrupted energy supplies? There is a growing conviction that buildings should be designed for passive survivability, today more commonly called **resilience**. Others prefer the word "adaptive" because we must now design buildings that can adapt to a changing climate.

For a building to be resilient it must be able to operate at least for a while without energy or water inputs from the outside, and it must be able to survive storms and floods. Because we heat, cool, and light buildings with energy, this book focuses only on resilience related to energy. Fortunately, sustainable buildings are more resilient because they require much less energy to operate through efficiency, passive design, and possibly on-site energy production. When power or other energy supplies are not available, resilient (i.e., sustainable) buildings will get only moderately cold in the winter and moderately hot in the summer, and they will be illuminated with daylight most of the day. Thus, from an energy standpoint resilience is just another argument for sustainable design.

1.7 BIOPHILIC DESIGN

The biophilia hypothesis states that human beings have a need for connection with living things such as pets, wild animals, plants, and views of nature. Recent research in neuroscience and endocrinology support what social research and traditional knowledge have long indicated: experiencing nature has significant benefits. Consequently, bringing nature into, onto, and around buildings is not a luxury but is instead important for health, productivity, energy conservation, and, crucially, as this book will show, aesthetics (Colorplates 27, 30, and 34).

1.8 COLOR AND ORNAMENTATION

White is the greenest color outdoors as well as indoors. White roofs have half the heat gain of black roofs. White walls also reduce heat gain, and in urban canyons they deliver more daylight to lower floors and the streets. White cities will experience cooler heat islands than typical cities. Indoors, white ceilings and walls reflect precious daylight and electric lighting. White is unquestionably the most sustainable color.

Polished metal and glass are also used as exterior wall finishes, but both materials perform more poorly than flat white. All-glass facades are popular, but without shading devices or light shelves they have disadvantages besides the most serious of poor energy performance. Whatever sunlight is not transmitted indoors or absorbed by the glass is reflected like a mirror to adjacent buildings and the ground below. This reflected sunlight causes serious glare and overheating where it was not expected, such as on the north facade of neighboring buildings. Flat white walls,

on the other hand, reflect some solar radiation back into space and the rest becomes a source of quality daylight for other buildings and the ground, which is especially important in urban areas. Glass buildings are also responsible for killing millions of birds each year. Because all-glass building facades are not energy efficient, they are not sustainable. The aesthetic of a facade should come from limited glazing, shading devices, light shelves, and ornamentation.

At its peak influence, modern architecture had no tolerance for ornamentation. Instead the emphasis was on form. Basing the aesthetic only on complex forms has strong energy implications, since more compact buildings are generally more sustainable. They require less material to build and less energy to operate for their lives. Thus, compact designs with ornamentation, small patches of color, or murals usually produce the most sustainable design (Fig. 1.8 and Colorplate 25). Fortunately, some types of ornamentation are again acceptable. The role of ornamentation in architecture is discussed by Brent C. Brolin in his book *Architectural Ornament: Banishment & Return*.



Figure 1.8 Exterior murals have become quite popular, especially in cities where the demolition of some buildings expose property line walls that were never meant to be seen. A type of mural called trompe l'oeil creates architectural illusions, as in this Chicago building. Such murals create "architecture" with a minimum of materials and energy.

1.9 ENERGY AND ARCHITECTURE

The heating, cooling, and lighting of buildings are accomplished by either adding or removing energy. Consequently, this book is about the manipulation and use of energy. In the 1960s, the consumption of energy was considered a trivial concern. For example, buildings were sometimes designed without light switches because it was believed that it was more economical to leave the lights on continuously. Additionally, the most popular air-conditioning equipment for larger buildings was the terminal reheat system, in which the air was first cooled to the lowest level needed by any space and then reheated as necessary to satisfy the other spaces. The double use of energy was not considered an important issue.

The building in which the author taught architecture for thirty years was built in 1974. At that time, the "rational economic decision" was to put no insulation in the walls since it would not pay for itself quickly enough. Today we think that decision was idiotic. Will our "rational economic decisions" today seem just as shortsighted thirty years from now?

Buildings now use about 40 percent of all the energy consumed in the United States for their operation. To construct them takes another 8 percent of all the energy. Clearly, then, the building industry has a major responsibility in the energy picture of this planet. Architects have both the responsibility and the opportunity to design in an energy-conserving manner.

The responsibility is all the greater because of the effective life of the product. Automobiles last only about ten years, and so any mistakes will not burden society too long. Most buildings, however, should have a

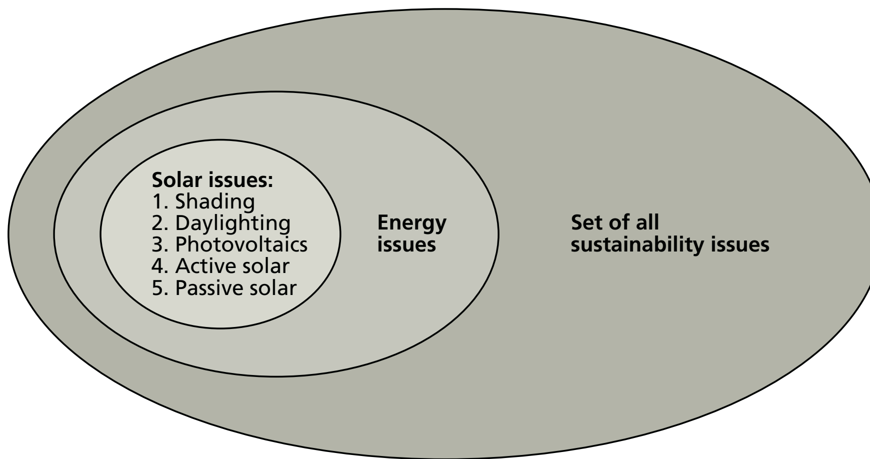


Figure 1.9 Sustainable design includes a large set of issues, and the energy issues are a large subset thereof. The solar issues are a much larger subset of the energy issues than most people realize. This image can be downloaded for free and used as a poster. It is available at www.heliodons.org.

useful life of at least fifty years. The consequences of design decisions now will be with us for a long time.

When people realize that the fossil energy that buildings consume causes global warming, the immediate reaction is to support the production of renewable energy that causes no pollution and no global warming. The quickest, most effective, and least expensive ways to fight global warming, however, come from using less energy.

Unfortunately, the phrase "energy conservation" has negative connotations. It makes one think of shortages and discomfort. Yet architecture that conserves energy can be comfortable, sustainable, humane, and aesthetically pleasing. It can also be less expensive than conventional architecture. Operating costs are reduced because of lower energy bills, and first costs are often reduced because of the smaller amount of heating and cooling equipment that is required. To avoid negative connotations, the more positive and flexible phrases "energy-efficient design" or "energy-conscious design" have been adopted to describe a concern for energy conservation in architecture. Energy-conscious design yields buildings that minimize the need for expensive, polluting, and nonrenewable energy. Because of the benefit to planet Earth, such design is now called sustainable, green, or low carbon.

Because of global warming, it is now widely recognized that reducing the energy appetite of buildings is the number one green issue. As Figure 1.9 illustrates, the energy issues are a very large subset of all of the sustainability issues. Figure 1.9 also demonstrates that the solar issues are a surprisingly large subset of the energy issues. One reason for this is that "solar" refers to many strategies: photovoltaics (solar cells), active solar (hot water), passive solar (space heating), daylighting, and shading. Although shading is the reverse of collecting solar energy, it is one of the most important solar design strategies, because it can save large amounts of air-conditioning energy at low cost.

1.10 CLIMATE AND ARCHITECTURE

In extreme climates, as are found in Russia and Indonesia, it is clear whether heating or cooling are the architect's main concern, but in temperate climates, buildings must be designed for both heating and cooling (Fig. 1.10a). However, the energy used and the money spent on heating or cooling are rarely equal in temperate climates. Figure 1.10b shows the heating and cooling degree-days, which predict the energy required for heating and cooling, for four

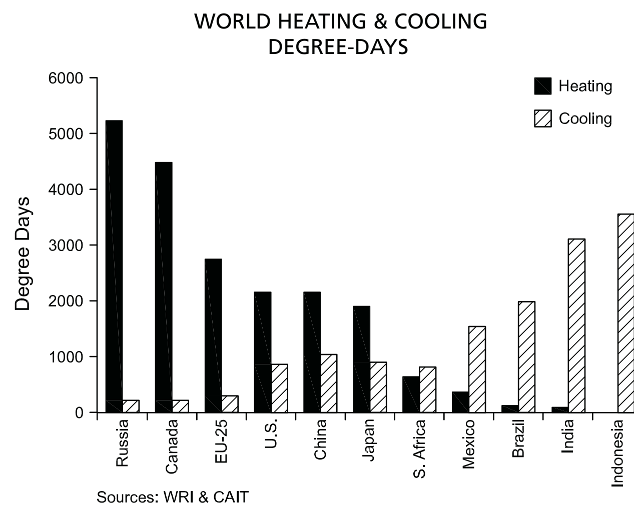


Figure 1.10a Heating and cooling degree-days predict how much energy (money) is required during the heating and cooling seasons. They can also be used to help set design priorities to achieve low energy climate responsive buildings.

American cities. For an explanation of degree-days, see Section 5.6(k).

Some aspects of building design are equally valid for both the heating and cooling loads. Insulation levels and an east-west building orientation reduce energy requirements in both summer and winter. However, other aspects of building design favor one season over another. For example, high ceilings are appropriate for a cooling-dominated climate while low ceilings are better for a heating-dominated climate. Because a building designed for its climate will be more energy efficient, it is important for the architect to know if heating or cooling loads dominate. For this reason, Chapter 5 gives detailed climate information for seventeen climate regions in the United States and Canada.

The problem of designing for a climate is further complicated because the heating and cooling loads vary with building type in the same climate. For example, an office building will have smaller heating and larger cooling loads than a house in the same climate. For simplicity, this book places building types into one of two categories: "internally dominated" buildings such as large office buildings and "envelope-dominated" buildings such as houses.

Because most people in the world live in hot climates, and because they are becoming wealthier, the use of air-conditioning is growing exponentially (Fig. 1.10c). Even in the United States,

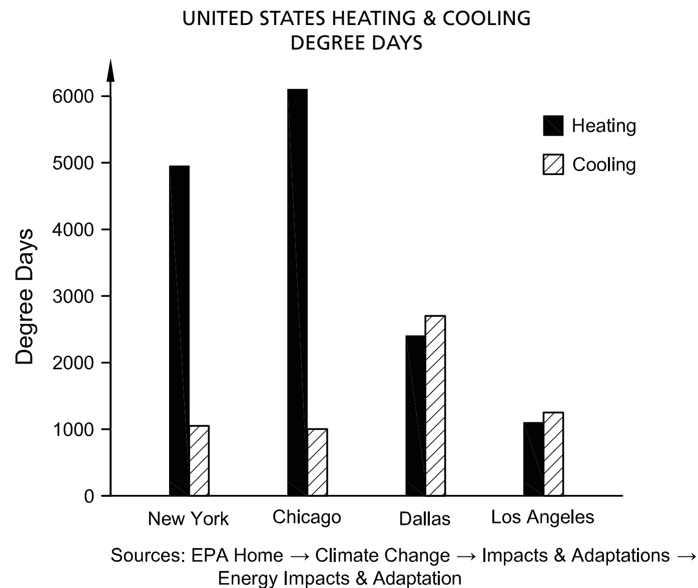


Figure 1.10b It may not be surprising that buildings in New York and Chicago need to emphasize the heating season, but it may be surprising that heating is also important in Dallas and Los Angeles. Note that the heating and cooling degree-days in those cities are almost equal.

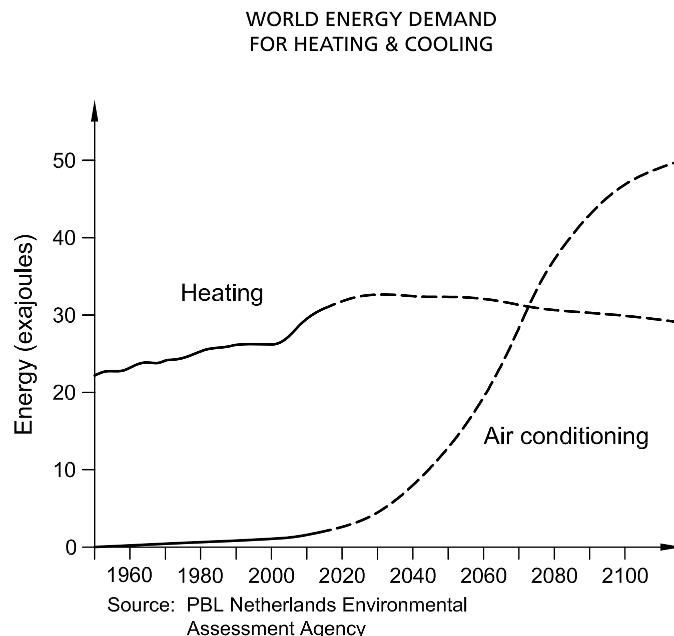


Figure 1.10c Because most people live in hot climates and because the number of people who can afford air conditioners is increasing rapidly, the energy needed for cooling is increasing exponentially. Thus, heat avoidance strategies such as shading will dominate future world architecture.

the energy for cooling is increasing as more people can afford it and as more people move to the South. To reduce the growth of energy consumption for air-conditioning, architects must focus on heat avoidance strategies such as shading and light colors.

1.11 SUSTAINABILITY CODES AND VOLUNTARY PROGRAMS

All over the world, codes and programs have been put in place to impel buildings to be low energy and low carbon. In the United States, the main codes are ASHRAE 90.1 and 189.1, the International Energy Conservation Code (IECC), and the International Green Construction Code (IGCC). However, it is mostly up to states and municipalities to pass laws that make codes mandatory.

To supplement the impact of codes, a number of programs have been created to spur the movement to low energy buildings. The most famous by far is Leadership in Environmental and Energy Design (LEED), created and run by the United States Green Building Council (USGBC). With each new version, the LEED program increases its focus on creating low energy buildings. The Green Building Initiative's Green Globes program is an alternative to LEED in the United States. Passive House is a rigorous program most appropriate to cold climates, and maybe the most demanding program of all is the Living Building Challenge.

The Environmental Protection Agency (EPA) of the United States government administers the voluntary **Energy Star** program, which produces ratings for products and appliances. The program also promotes efficient building methods.

Another method for encouraging sustainable design is to give awards. Every year the American Institute of Architecture Committee on the Environment (AIA/COTE) announces the "Top Ten" from all the submissions of sustainable design it receives. Energy responsiveness is an important criterion.

Perhaps the most important organization for making buildings adapt to climate change is Architecture 2030. In 2006 it issued the 2030 Challenge, which would reduce greenhouse gas emissions of buildings to zero by 2030 in steps—70 percent reduction by 2015, 80 percent reduction by 2020, 90 percent reduction by 2025, and 100 percent reduction by 2030. The 2030 Challenge has been adopted by the AIA; the U.S. Council of Mayors; the National Association of Governors; the U.S. Green Building Council; the U.S. government, which requires all new and renovated federal buildings to meet the challenge (2007 Energy Independence and Security Act); and numerous other governmental, for-profit, and nonprofit organizations.

The reader is encouraged to visit Architecture 2030s website: www.architecture2030.org.

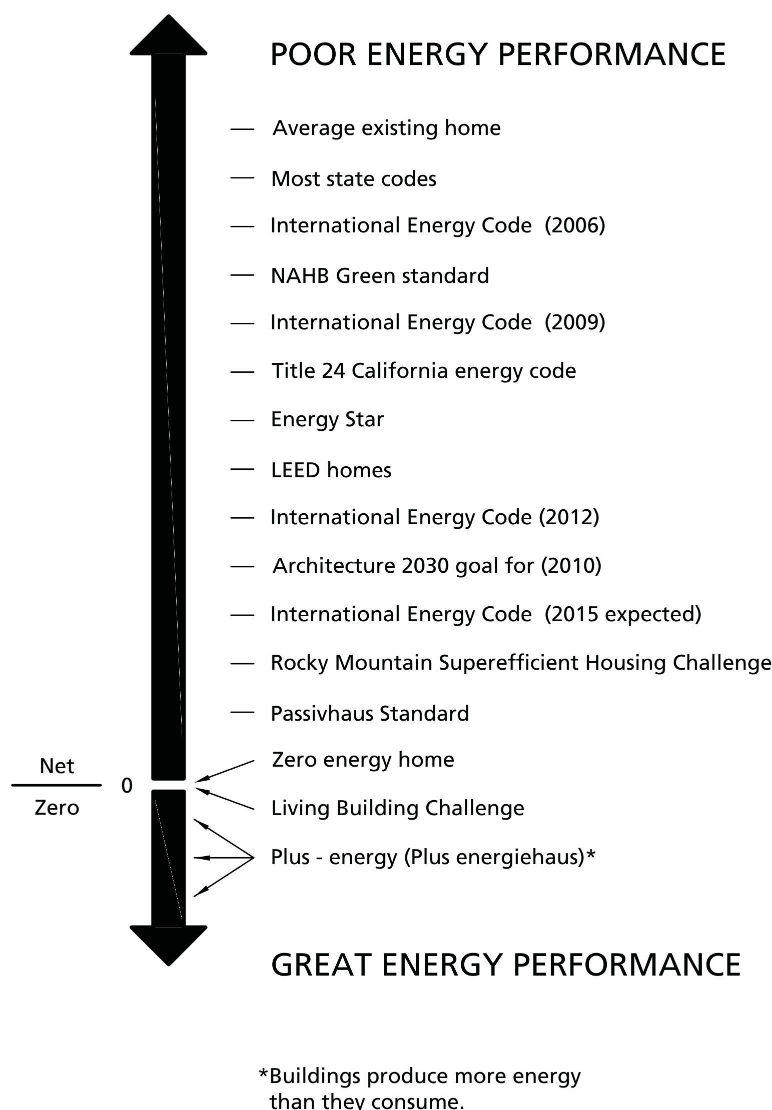


Figure 1.11 The energy performance of buildings constructed under the influence of energy codes and voluntary programs varies greatly, as this diagram indicates. The ranking is based on the Home Energy Rating System (HERS) index. (After the Rocky Mountain Institute.)

The combination of codes and voluntary programs is having a profound effect on how America builds. See Figure 1.11 on how the various codes and programs compare in achieving great energy performance.

1.12 INTEGRATED DESIGN

Buildings have become too complex for any one individual to design, and the need for sustainability has further increased the complexity of buildings. The traditional linear design process, where the various building professions make their contributions sequentially, is not suited to creating high-performing buildings (Fig. 1.12a). In such a design process, the various building systems are not able to work together most efficiently. Instead, they are often competing with one another. For example, an all-glass facade will result in a huge energy guzzling mechanical system. In the sequential design process, it is usually too late to redesign the glass facade when the mechanical equipment is being designed and found to be excessively large. In the integrated whole-building design process, on the other hand, the needs of the various systems are considered at the very beginning of the architectural design so that they can all work

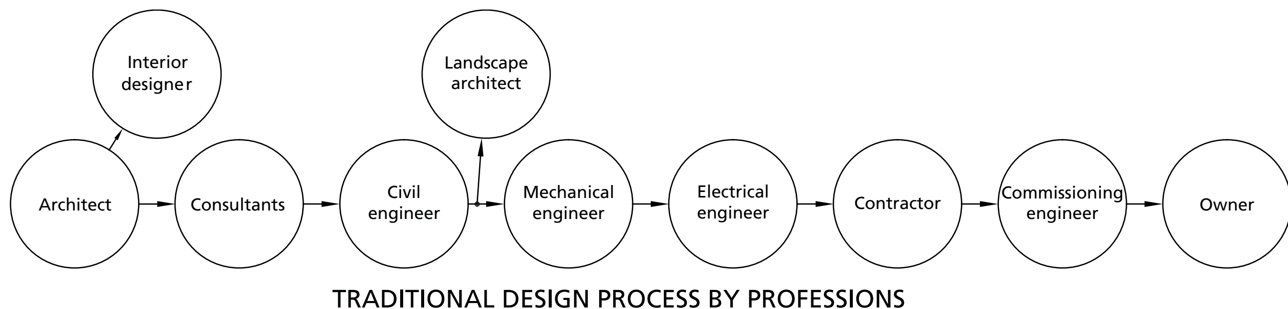


Figure 1.12a In the traditional linear design process, the various building design professionals work on a project sequentially. Unfortunately, this method does not promote the design of high-performing sustainable buildings.

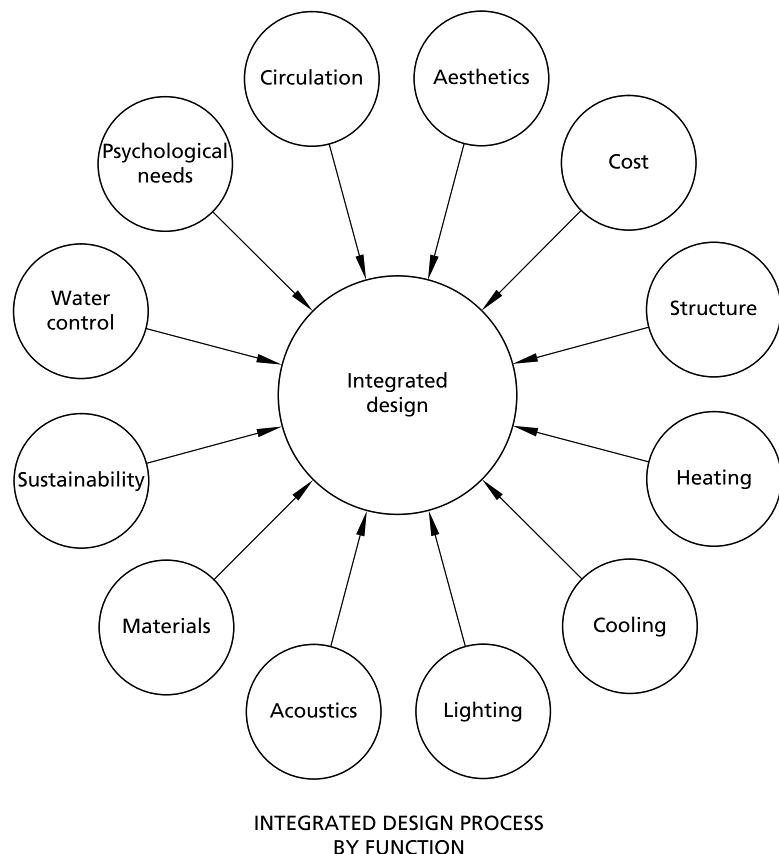


Figure 1.12b In the whole-building integrated design process, the needs of the various building systems are considered from the very beginning of the design process. The resultant designs are then harmonious with the needs of the various systems to create high-performance buildings. It also makes possible synergies that further improve the performance and sustainability of a project.

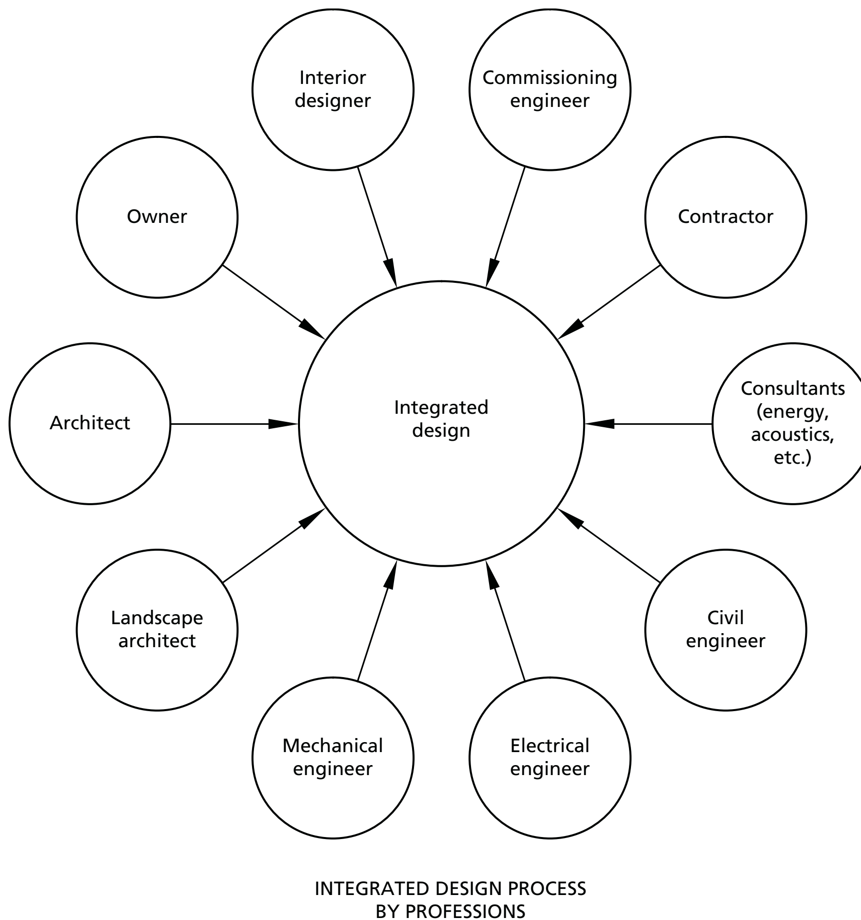


Figure 1.12c The integrated design process requires the key building professionals to work as a team even before the first line on the first drawing is made. The architect is then able to create a whole-building design with high performance.

together to create a high-performance building (Fig. 1.12b). For example, the heating and cooling loads on the mechanical equipment influence not only the facade design but also the orientation and form of the building. For the various building systems to work together, the appropriate professionals must form a team that together creates the design (Fig. 1.12c). The team must start meeting before the first line is drawn because that first line has so many significant consequences.

1.13 DECISION MAKING

The design process is essentially a decision-making process based on asking the right questions in the right order. For example, the first line in the first drawing should be made only after the many consequences of the building's location, orientation, and length have been considered. That first line will have great impact on the heating, cooling, and lighting energy that that building will consume. The wrong orientation of a building, for instance, will have great negative consequences later on when design decisions are made about shading, passive solar, and daylighting.

The set of decisions necessary to create a sustainable building can be divided into three subsets: decisions for which a clear-cut best answer exists; decisions which are not clear-cut but modeling can give the best answer; and decisions which are essentially subjective (Fig. 1.13). The architect and other building professionals should be aware of the issues that are clear-cut, and they should start the design process using these proven ideas. To use an extreme example, in designing a car the decision that the wheels should be round must come at the beginning. It is not necessary to model square wheels to find out if they are the best choice. Indeed, it is not appropriate to use square wheels even if they are visually more consistent with a square body. The shape of the wheels is not open to a subjective decision. Similarly, to create high-performance sustainable buildings most subjective decisions should made only after the important objective decisions have been considered.

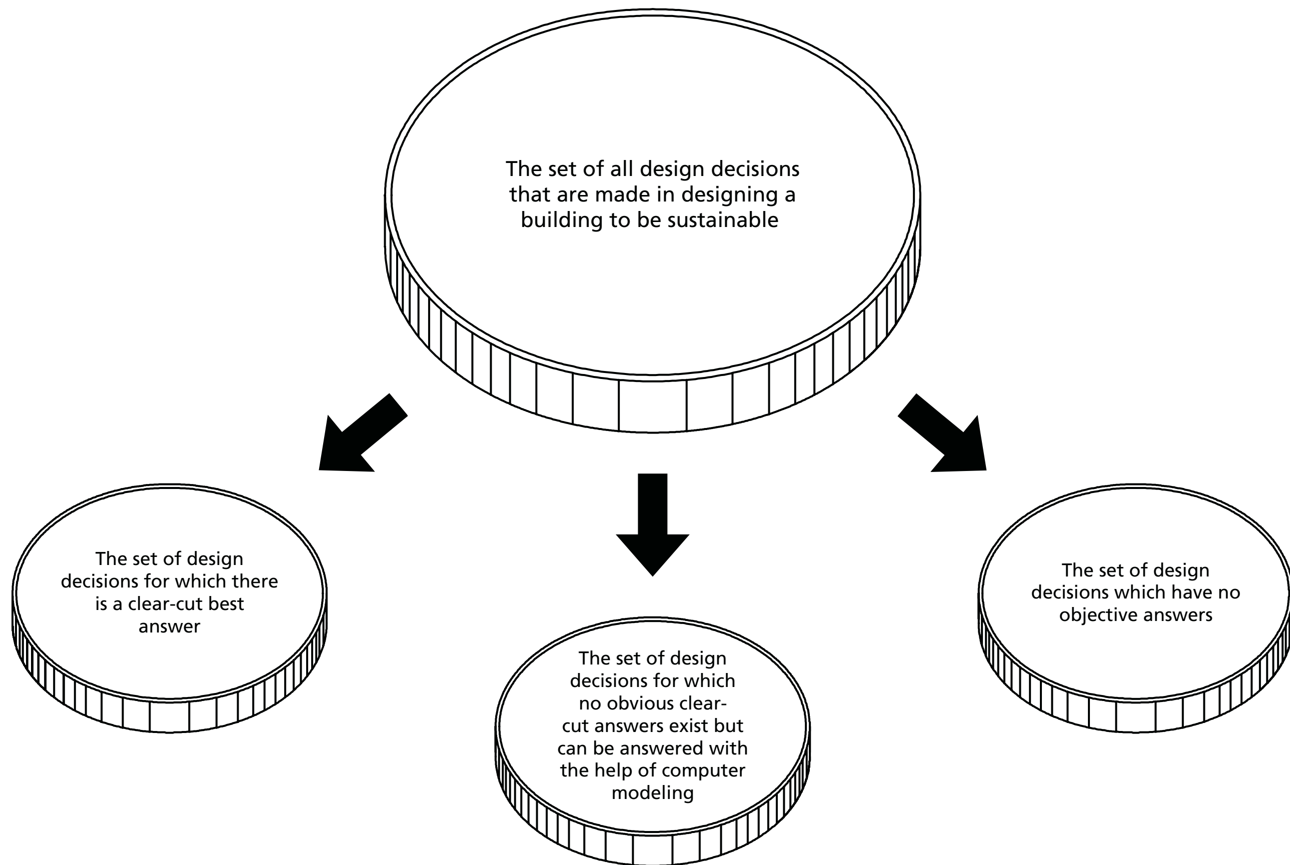


Figure 1.13 To create a high-performing, sustainable building, the decisions made at the beginning of the schematic design stage are critical. The decisions based on hard, well-known principles should be made first, and the decisions based on subjective principles should be made last.

1.14 CONCLUSION

The following design considerations have an impact on both the appearance and the heating, cooling, and lighting of a building: form, orientation, compactness (surface-area-to-volume ratio), size and location of windows, and the nature of the building materials. Thus, when architects draw the first line at the schematic design stage to design a building, they simultaneously start the design of the heating, cooling, and lighting. Because of this inseparable relationship between architectural features and the heating, cooling, and lighting of buildings, we can say that the environmental controls are form-givers in architecture.

It is not just tiers one and two that have aesthetic impact. The mechanical equipment required for heating and cooling is often quite bulky, and because it requires access to outside air, it is frequently visible on the exterior. The lighting equipment, although less bulky, is even more visible. Thus, even tier three is interconnected with the architectural aesthetics, and, as such, must be considered at the earliest stages of the design process.

KEY IDEAS OF CHAPTER 1

1. Both vernacular and formal architecture were traditionally designed to respond to the heating, cooling, and lighting needs of buildings.
2. Borrowing appropriate regional design solutions from the past (e.g., the classical portico for shade) can help in creating sustainable buildings.
3. In the twentieth century, engineers dealing with mechanical and electrical equipment had the primary responsibility for the environmental needs of buildings. Architects had provided for these needs in the past, and they can again be important players in the future.

4. The heating, cooling, and lighting needs of buildings can be designed by the three-tier approach:

   TIER ONE: the basic design of the building form and fabric (by the architect)
   TIER TWO: the design of passive systems (mostly by the architect)
   TIER THREE: the design of the mechanical and electrical equipment (by the engineer).

5. Buildings use about 40 percent of all the energy consumed in the United States. Their construction takes another 8 percent.
6. Currently, the dynamic mechanical equipment responds to thecontinually changing heating, cooling, and lighting needs of a building. There are both functional and aesthetic benefits when the building itself is more responsive to the environment (e.g., movable shading devices). Buildings should be dynamic rather than static.
7. Sustainable buildings also provide resilience ("passive survivability") in case of power outages or high fuel costs.
8. Sustainable buildings should also be adaptive by anticipating a more severe climate due to global warming.
9. Sustainable buildings should consider biophilia for both functional and psychological reasons.
10. White is the greenest color. Roofs and walls should be white in order to create cooler buildings and cooler cities.
11. Because a compact "shoebox" building is often the most sustainable form, color and ornamentation should be used to create interest.
12. Energy codes are necessary to make most buildings more energy efficient. Voluntary programs like LEED are helping to change the worldview of the building industry.
13. The integrated whole-building approach to design creates much higher performing, more sustainable buildings.
14. The design process is a decision-making process. The early decisions in the process are the most important because they affect the available options later on.
15. Because of global warming, it is imperative that buildings use less energy and achieve zero greenhouse gas emissions by 2030.
16. There is great aesthetic potential in energy-conscious architecture.

Resources

FURTHER READING

See the Bibliography in the back of the book for full citations.

Banham, R. *The Architecture of the Well-Tempered Environment*.
Brown, G. Z., and M. DeKay. *Sun, Wind, and Light: Architectural Design Strategies*.
Cox, S. *Losing Our Cool*.
Duly, C. *The Houses of Mankind*.
Fathy, H. *Natural Energy and Vernacular Architecture: Principles and Examples with Reference to Hot Arid Climates*.
Fitch, J. M. *The Architecture of the American People*.
———. *Shelter: Models of Native Ingenuity*.
Fitch, J. M., and W. Bobenhausen. *American Building: The Environmental Forces That Shape It*.
Heschong, L. *Thermal Delight in Architecture*.
Konya, A. *Design Primer for Hot Climates*.
Lovins, Amory. "More Profit with Less Carbon."
Lovins, Amory, et al. *Winning the Oil Endgame*. www.oilendgame.com.
McDonough, W., and M. Braungart. *The Next Industrial Revolution*.
Nabokov, P., and R. Easton. *Native American Architecture*.
Olgyay, V. *Design with Climate: Bioclimatic Approach to Architectural Regionalism*.
Rapoport, A. *House Form and Culture*.
Rudofsky, B. *Architecture without Architects: A Short Introduction to Non-Pedigreed Architecture*.
———. *The Prodigious Builders: Notes Toward a Natural History of Architecture*.
Stein, R. G. *Architecture and Energy: Conserving Energy Through Rational Design*.
Susanka, S., and K. Obolensky. *The Not So Big House: A Blueprint for the Way We Really Live*.
Taylor, J. S. *Commonsense Architecture: A Cross-Cultural Survey of Practical Design Principles*.

PAPERS

Knowles, R. "On Being the Right Size." www.rcf.usc.edu/~rknowles.
———. "Rhythm and Ritual." www.rcf.usc.edu/~rknowles.
———. "The Rituals of Place." www.rcf.usc.edu/~rknowles.

ORGANIZATIONS

Architecture 2030, www.Architecture2030.org
GreenSource, www.greensource.construction.com
Environmental Building News (EBN), www.buildinggreen.com/news
Rocky Mountain Institute, www.rmi.org

CHAPTER 2

SUSTAINABLE DESIGN AND ENERGY SOURCES

We should be concerned about the future, because we have to spend the rest of our lives there.

Francis Kettering,
American investor, engineer, businessman, and philanthropist

Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs.

The United Nations World Commission on Environment and Development, the Brundtland Report, 1987

As we peer into society's future, we—you and I, and our government—must avoid the impulse to live only for today, plundering, for our own ease and convenience, the precious resources of tomorrow. We cannot mortgage the material assets of our grandchildren without risking the loss also of their political and spiritual heritage. We want democracy to survive for all generations to come, not to become the insolvent phantom of tomorrow.

President Dwight D. Eisenhower's Farewell Address, 1961

2.1 EASTER ISLAND: LEARNING FROM THE PAST

Easter Island has long mystified archaeologists. When the tiny, remote island 2,000 mi (3,200 km) from the nearest continent was "discovered" on Easter day in 1722, about two hundred mammoth stone statues, some more than 30 ft (9 m) tall and weighing more than 80 tons (73 metric tons), stood on the island [Fig. 2.1].

The island was a biological wasteland. Except for introduced rats and chickens, there were no animal species higher than insects. Only a few dozen plant species—mostly grasses and ferns—lived on the island, and nothing was more than 10 ft (3 m) in height. There was no obvious way that the island's 2,000 or so inhabitants could have transported and hoisted the huge statues.

Based on an analysis of ancient pollen, researchers have now established that Easter Island was a very different place when the Polynesians first arrived there around A.D. 400. In fact, it was a subtropical paradise, rich in biodiversity. The Easter Island palm grew more than 80 ft (24 m) tall and would have been ideal for carving into canoes for fishing, as well as into equipment for erecting statues. In addition to the rich plant life, there were at least twenty-five species of nesting birds.

We now believe that Easter Islanders exploited their resources to the point that they exterminated all species of higher animals and many species of plants. The island's ecosystem might have been destroyed in a cascading fashion; as certain birds were eliminated, for example, trees dependent on those birds for pollination could no longer reproduce. Denuded of forests, the land eroded, carrying nutrients out to sea.

Researchers believe that the island population had grown to a peak of 20,000 that lived in a highly organized structure. But as food (or the ability to get it) became scarce, this structure broke down into warring tribal factions. By 1722, the island's population had dropped to 2,000.

Why didn't the Easter Islanders see what was happening? Jared Diamond, in the August 1995 *Discover* magazine, suggests that the collapse happened "not with a bang but a whimper." Their means of making boats, rope, and log rollers disappeared over decades or even generations and either they didn't see what was happening or couldn't do anything about it.

Will humanity as a whole do better with planet Earth than the Polynesian settlers did with their Easter Island paradise? Many politicians and talk-show hosts claim that there are no limits to growth—that environmental doomsayers are wrong. But Easter Island shows us that limits are real. Let's not wait until it is too late to come to grips with these limits.

Shortened by permission from Alex Wilson, editor and publisher, Environmental Building News (EBN). *The full article appeared in* EBN *4, no. 5 (September–October 1995).* EBN *is a monthly newsletter for architects and builders committed to improving the sustainability of buildings and the built environment (see Appendix K). This material can also be found in Jared Diamond's* Collapse: How Societies Choose to Fail or Succeed, *2011.*



Figure 2.1 The mysterious stone heads of Easter Island. (Drawn by Ethan Lechner)

2.2 SUSTAINABLE DESIGN

In the long run, sustainable design is not an option but a necessity. Earth, with over 7.2 billion people, is rapidly approaching the same level of stress that 20,000 people caused to Easter Island. We are literally covering planet Earth with people (Fig. 2.2a). We are depleting our land and water resources; we are destroying biodiversity; we are polluting the land, water, and air; and we are changing the climate, with potentially catastrophic results.

In the short term, it may seem that we do not have to practice sustainable design, but that is only true if we ignore the future. We are using up resources and polluting the planet without regard to the needs of our children and our children's children (Fig. 2.2b).



Figure 2.2a Nighttime lights of the world as viewed from satellites clearly show how people are filling up the planet. Much of the dark land is uninhabitable (e.g., the Sahara and the Tibetan Plateau). (From NASA.)



Figure 2.2b Where a mountain once stood, a colossal hole now exists. Human beings are literally moving mountains to feed their appetite for resources. For a sense of scale, note the trains on the terraces on the far side. The tunnel at the bottom of this open-pit copper mine in Utah is for the trains to take the ore to smelters beyond the mountains.

Already in 1993, the World Congress of Architects in Chicago, said:

> Sustainability means meeting the needs of the current generation without compromising the ability of future generations to meet their own needs. A sustainable society restores, preserves, and enhances nature and culture for the benefit of all life present and future; a diverse and healthy environment is intrinsically valuable and essential to a healthy society; today's society is seriously degrading the environment and is not sustainable.

Many ways exist to describe sustainable design. One approach urges using the four Rs (Fig. 2.2c):

REDUCE
REUSE
RECYCLE
REGENERATE

This book will focus on the first R: reduce. Although the word "reduce" might evoke images of deprivation, it applies primarily to the reduction of waste and extravagance. For example, American houses have more than doubled in size since 1950, and since families are now smaller, the increase in size per person is about 2.8 times (Fig. 2.2d). Is that really necessary? Are Americans happier today than in 1950? Are "starter castles" and "McMansions" the route to happiness? Are Americans happier than the British or French who live in significantly smaller homes? The book *The Not So Big House*, written by the architect Sarah Susanka, was a national best seller. Many people have discovered that bigger is not better much of the time. Susanka believes that it is wiser to build a smaller,

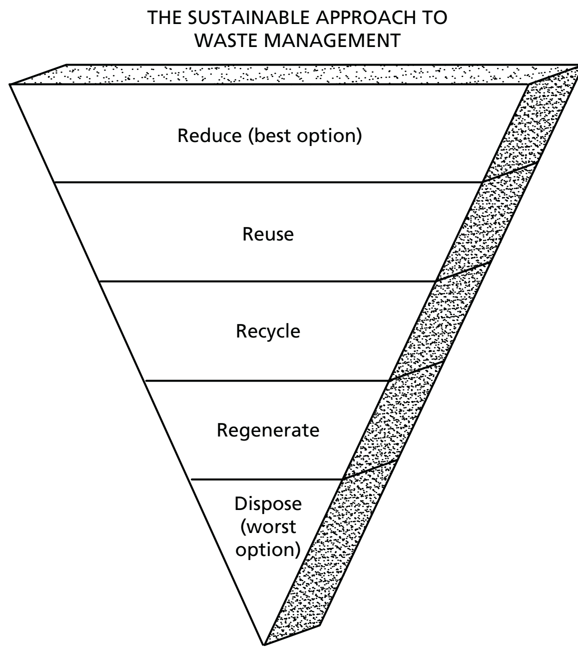


Figure 2.2c The size of each tapering block represents the relative importance of each approach to sustainability, with "reduce," as in smaller houses, being the best option.

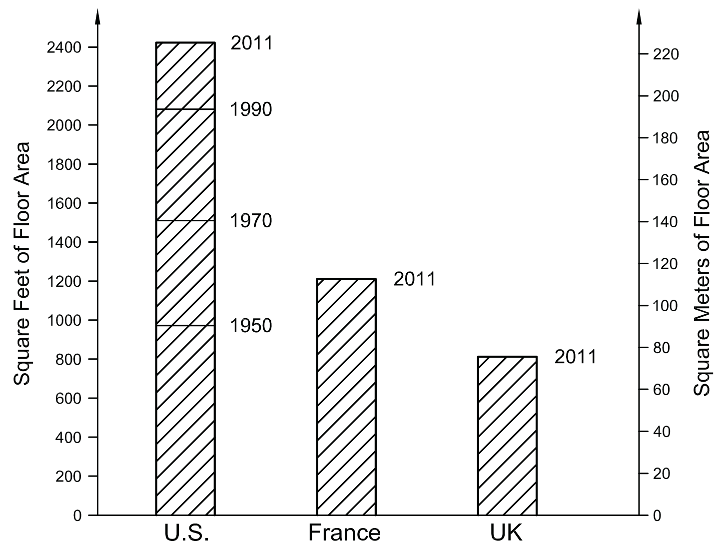


Figure 2.2d Contemporary houses in the United States are much larger than those in France, the United Kingdom, or larger houses in the United States of the 1950s. Unfortunately, not only are today's large less sustainable, but also there is no indication that larger houses have produced more happiness.

high-quality home than the more typical larger, low-quality one of the same cost. Furthermore, a small standard house is more sustainable than even a very energy-efficient large house, because it will have less embodied energy and a smaller surface area with fewer windows for heat gain and loss. Unfortunately, an incorrect use of the energy utilization index (EUI) and many other evaluation tools would show the larger house as more efficient and therefore more sustainable (see Sidebox 2.2).

Besides reducing the size of buildings, we can also reduce their energy appetite. Consider how inefficient a conventionally built home is, when a demonstration home in Lakeland, Florida, wastes 80 percent less energy (FSEC, 1998). Proven techniques in the areas of heating, cooling, and lighting can easily reduce energy use in buildings by 50 percent, and with a little effort 80 percent reductions are possible. We already have the knowledge, tools, and materials necessary to design ultra-low-energy buildings, and some of the known design strategies are equivalent to a free lunch. For example, strategies such as orientation and color can save much energy and cost nothing.

Although the primary focus of this book is "reduce" (i.e., make more efficient) by design, the building industry can also make use of the other three sustainability techniques, which will be briefly discussed in the next section.

SIDEBOX 2.2

The Energy Utilization Index (EUI), created by the U.S. government, is defined as the amount of energy used for heating and cooling per square foot per year.

$$\text{EUI} = \text{kBtu/ft}^2 \bullet \text{year}$$

where kBtu = 1000 British thermal units

The EUI is only useful for comparisons of buildings of the same type (e.g. offices, houses, schools) and of similar size. Furthermore, adjustments must be made for different climates.

Other measurement systems include:

Site energy used = utility-measured energy
Source energy = total amount of raw energy required to operate a building

2.3 REUSE, RECYCLE, AND REGENERATE BY DESIGN

Figure 2.3a shows a sight that is much too common: a building being demolished. Instead, it should in most cases be renovated and reused. According to one study, "in almost all cases, retrofit yields better environmental outcomes than demolition and new construction."[1] It takes from twenty to eighty years for a new energy-efficient building

[1]From a study coauthored by the National Trust for Historic Preservation and the Cascadia Green Building Council, *The Greenest Building: Quantifying the Environmental Value of Building Reuse*.



Figure 2.3a Buildings marked for demolition should be either reused through renovation or recycled through the process of deconstruction.



Figure 2.3b The Center for Regenerative Studies at Cal Poly Pomona was established to teach and explore how to restore the planet. The buildings are all oriented to the south, with few if any windows facing east or west. The roofs also face south to support active solar hot water collectors and future photovoltaic panels.



Figure 2.3c Fruit-bearing plants are used for shading at the Center for Regenerative Studies. (Photo by Walter Grondzik.)

to compensate for the environmental loss of the building it replaces. For most building types, it takes about twenty-five years before the savings in operating energy equals the energy required to build anew.

Although this book focuses on significantly reducing the operating energy required by buildings, it is almost as important to reduce the embodied (embedded) energy required to build new buildings because that energy has an immediate effect on global warming. A major tool for reducing the embodied energy is the technique of life cycle assessment (LCA), which tries to determine the environmental and resource impacts of a material, product, or even a whole building over its lifetime. A major part of the assessment is to determine the embodied energy. The green-building program LEED v4 includes life cycle assessment.

Also, as architect Carl Elefante has said, "New green buildings are not reducing global warming; they are only reducing the growth of global warming. Instead, fixing buildings can reduce global warming."

"The greenest building is the one that already exists!"
—Carl Elefante, architect

Even if the building in Figure 2.3a could not be saved, it could still be recycled. By a process of deconstruction, it could be taken apart, and its component parts could be either recycled (concrete, steel, lumber, etc.) or reused (windows, doors, bricks, etc.). Instead, most buildings end up as landfill, with their resources and embodied energy (see Section 3.23) completely lost.

The fourth R, regenerate, deals with the fact that much of the earth has already been degraded and needs to be restored. Since little is known about how to restore the earth, the Center for Regenerative Studies was established at Cal Poly Pomona through the pioneering work of John T. Lyle (Fig. 2.3b). Participating students from Cal Poly Pomona reside on-site to investigate how to live a sustainable and regenerative lifestyle. Built on a former landfill site, both the landscape and the architecture of the center were carefully designed to demonstrate and explore green and restorative techniques (Fig. 2.3c).

2.4 THE SUSTAINABILITY MOVEMENT

The issues related to sustainability are so all-encompassing that many feel that a different word should be used. The word "green" is often used because its connotations are flexible and it symbolizes nature, which truly is sustainable. For the same reason, many use the word "ecological." Still others prefer the phrase "environmentally responsible." The words might be different, but the goals are the same.

In "The Next Industrial Revolution" (*Atlantic Monthly*, Oct. 1998), architect William McDonough and scientist Michael Braungart suggest that sustainability is based on the following three principles:

1. *Waste equals food*—Everything must be produced in such a manner that, when its useful life is over, it becomes a healthy source of raw materials to produce new things.
2. *Respect diversity*—Designs for everything will respect the regional, cultural, and materials of a place.
3. *Use solar energy*—All energy sources must be nonpolluting and renewable, and buildings must be solar responsive.

The world community is becoming increasingly aware of the seriousness of our situation, and many important steps have been taken. The most successful so far has been the Montreal Protocol of 1987, through which the world agreed to rapidly phase out chlorofluorocarbons, which are depleting the ozone layer, thereby exposing the planet to more harmful ultraviolet radiation. Because the danger was clear and imminent, the world's resolve was swift and decisive.

Other important gatherings have addressed the need for environmental reform. In 1992, the largest gathering of world leaders in history met at the Earth Summit in Rio de Janeiro to endorse the principle of sustainable development. In 1997, representatives of many countries met in Kyoto to agree on concrete measures to address global warming. Other world summits on climate change were Bali 2007, Copenhagen 2009, and Warsaw 2013. Some countries, such as Germany, have decided to make sustainability a national goal for several reasons: it is the moral action that they owe to the children of the world, for their national security, and for economic reasons. In the United States, the American Institute of Architects has set up the Committee on the Environment (COTE) to help architects understand the problems and shape the responses needed for creating a sustainable world.

2.5 POPULATION AND AFFLUENCE

By the end of 2013, the population of the earth was more than 7.2 billion. There are various estimates on the rate of population growth, as seen in Figure 2.5a. It is appropriate to ask how many people the earth can hold. The answer to that question depends on the response to further questions. Is the capacity of the earth to be sustainable, and what is to be the standard of living?

The sustainable population or carrying capacity of the earth might already have been exceeded. Global warming is one indicator that we have exceeded the planet's carrying capacity.

Another indicator is the amount of freshwater available for the growing world population. Many parts of the world are using water faster than it is replenished. Figure 2.5b shows the problem in the American Southwest.

Scientists Paul Ehrlich and John Holden proposed the following relationship:

$$I = P \times A \times T$$

where

I = environmental impact
P = population
A = affluence per person
T = technology

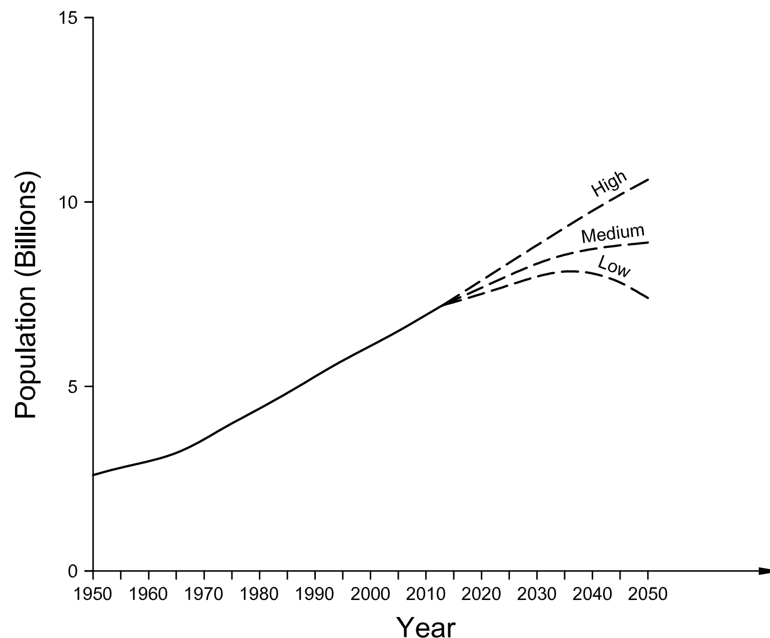


Figure 2.5a Since population growth cannot be predicted precisely, the United Nations publishes a projected range from high to low.



Figure 2.5b The "bathtub ring" visible in this view of Lake Mead indicates that water is being used up faster than the Colorado River can replenish it.

This relationship clearly shows that the greater the population, the greater the impact on the environment. It also shows that the more affluent a society, the greater the impact on the environment. For example, a family that lives in a 2500 ft^2 (225 m^2) house affects the environment far more than a family that lives in a 1000 ft^2 (90 m^2) house. Thus, it should be noted that for a given impact on the environment, the greater the population, the lower its affluence must be. Consequently, the higher a standard of living we want, the greater the need to stop population growth.

Technology also has a great impact on the environment. A person today will have a much greater impact on the environment than did a person a couple of centuries ago, when there were no automobiles, air travel, air-conditioning, electrical appliances, electrical lighting, etc. So far, most technology has had a negative impact on the environment. We can change that situation, and this book shows how to use technology that is more benign. Although not the purpose of this book, it must be recognized that sustainability cannot be achieved only by good technology; it requires us to change our values so that a high quality of life is not equated with high consumption. We also need to understand that trying to create a high standard of living for the inhabitants of the world without population control "is as though one attempted to build a 100-story skyscraper from good materials, but one forgot to put in a foundation" (Bartlett, 1997).

2.6 GROWTH

As we have seen, the growth of population, affluence, and technology places great stress on the planet by causing growth in the use of petroleum, wood, concrete, water, and just about everything else.

How is it, then, that we generally think positively about growth? Most politicians get elected by promising growth. Most communities think that 5 percent annual growth is a great idea, but do they realize that with steady 5 percent growth per year, the community will double in size every fourteen years? The doubling time for any fixed growth rate is easy to determine. See Sidebox 2.6.

Growth is popular for several reasons: many people make a good living based on growth, we generally think bigger is better, and we don't fully understand the long-term consequences of growth.

Let us look to nature for guidance on what kind of growth we want. Most living things grow until they mature. In nature, unlimited growth is seen as pathological. As the environmental writer Edward Abbey noted: "Growth for the sake of growth is the ideology of the cancer cell." Nature suggests that growth should continue until a state of maturity is reached, whereupon the focus should be on improving the quality and not the quantity.

A steady growth rate does not result in steady growth. This misconception is a major reason for our inability to plan properly for the future. For example, if the world population continues growing at its 1.9 percent rate (a small rate?) from 1975, it will grow to a size where there will be one person for every square meter (approximately a square yard) of dry land on earth in only 550 years (Bartlett, 1978). This is an example of the power of exponential growth.

SIDEBOX 2.6

To determine the doubling time for any fixed rate of growth, use the following equation:

$$T_2 = 70/G$$

where

T_2 = doubling time
G = growth rate in percent

2.7 EXPONENTIAL GROWTH

Since this book is about heating, cooling, and lighting, let us look at the growth of energy consumption over the last 10,000 years (Fig. 2.7). As in all exponential curves, growth is very slow for a very long time. Then, all of a sudden, growth becomes very rapid and then almost instantly out of control. Because the implications of exponential growth are almost sinister, it is important to take a closer look at this concept.

We have a very good intuitive feel for straight-line relationships. We know that if it takes one minute to

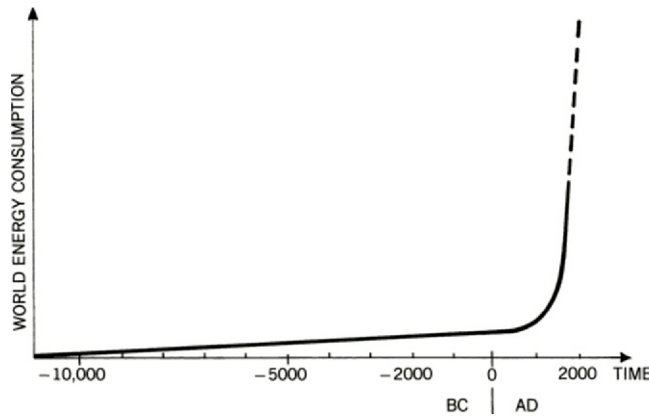


Figure 2.7 The exponential growth in world energy consumption and population growth are very similar.

fill one bucket of water, it will take five minutes to fill five such buckets. We do not, however, have that kind of intuitive understanding of nonlinear (exponential) relationships. Yet, some of the most important developments facing humankind involve exponential relationships. Population, resource depletion, and energy consumption are all growing at an exponential rate, and their graphs look very much like Figure 2.7.

2.8 THE AMOEBA ANALOGY*

Suppose a single-celled amoeba splits in two once every minute. The growth rate of this amoeba would be exponential, as Figure 2.8a illustrates. If we graph this growth, it yields the exponential curve seen in Figure 2.8b. Now let us also suppose that we have a certain size bottle (a resource) that would take the reproducing amoebas ten hours to fill. In other words, if we put one amoeba into the bottle and it splits every minute, then in ten hours the bottle will be full of amoebas, and all the space will be used up.

Question: How long will it take for the amoebas to use up only 3 percent of the bottle?

A. 18 minutes (3 percent of 10 hours)
B. about 1 hour
C. about 5 hours
D. about 8 hours
E. 9 hours and 55 minutes

Since each amoeba doubles every minute, let us work backward from the end.

Time	Percentage of bottle used up	
10:00	100	
9:59	50	
9:58	25	
9:57	12	
9:56	6	
9:55	3	Answer

For the amoebas, the space in the bottle is a valuable resource. Do you think the average amoeba would have listened to a doomsayer who at nine hours and fifty-five minutes predicted that the end of the "bottle space" was almost upon them? Certainly not—it would have laughed. Since only 3 percent of the precious resource is used up, there is plenty of time left before the end.

Of course, some enterprising amoeba went out and searched for

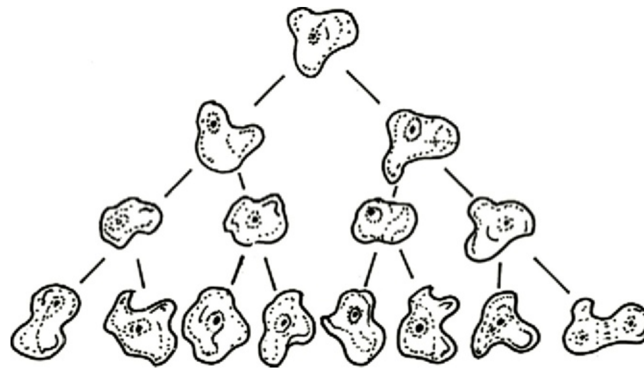


Figure 2.8a The exponential growth of an amoeba colony.

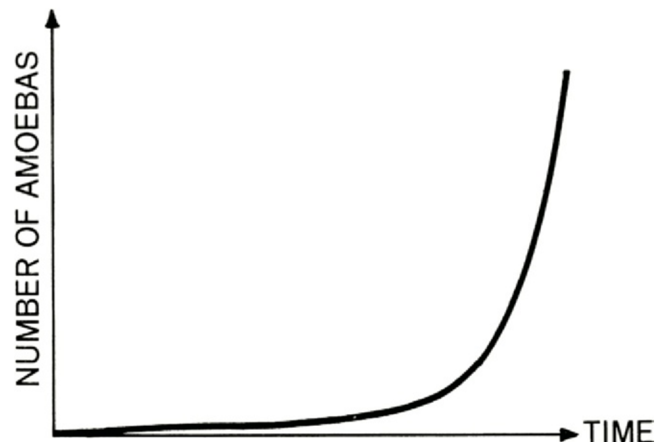


Figure 2.8b The theoretical exponential growth of an amoeba colony.

*Based on the work of Albert A. Bartlett (Bartlett, 1978).

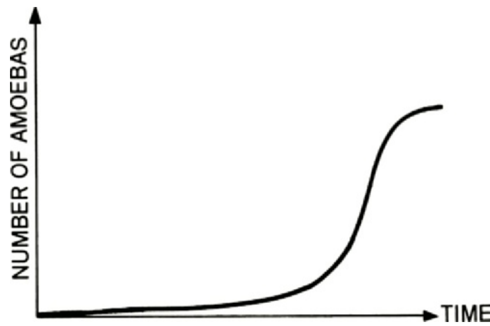


Figure 2.8c The actual growth of an amoeba colony.

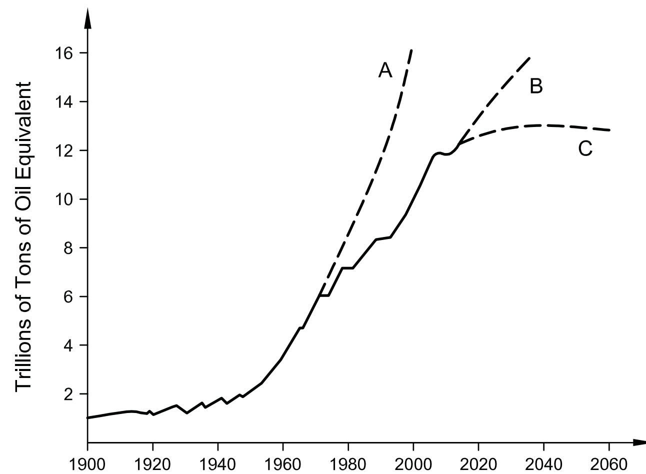


Figure 2.8d Alternate paths for future world energy consumption: (A) historical trend not followed because of the 1973 energy crisis; (B) trend if old wasteful habits return; (C) trend if conservation and efficiency guide our policies. (After "State of the World, 1999" and International Energy Agency, "World Energy Outlook," 2011.)

more bottles. If it found three more bottles, then the amoebas increased their resource to 400 percent of the original. Obviously, that was a way to solve their shortage problem. Or was it?

Question: How much additional time was bought by the 400 percent increase?

Answer: Since the amoebas double every minute, the following table tells the sad tale.

Time	Percent of the bottle filled
10:00	100
10:01	200
10:02	400

The amoebas gained only two more minutes by finding three more bottles. Obviously, it is hopeless to try to supply the resources necessary to maintain exponential growth at its later stages. What, then, is the solution?

In nature, there is no such thing as limitless exponential growth. For example, the growth of the amoeba actually follows an S curve. Although growth starts at an exponential rate, it quickly levels off, as seen in Figure 2.8c. The amoebas not only run out of food but also poison themselves with their excretions. Since humans are not above nature, they cannot support exponential growth very long either. If people do not control their growth willingly, nature will take over and reduce growth by such timeless measures as pollution, shortages, famine, disease, and war.

Until 1973, the growth of energy consumption followed the exponential curve A in Figure 2.8d. Then, with the beginning of the energy crisis of 1973, energy consumption followed an S-shaped curve. Initially the shortages and later the implementation of efficiency strategies dramatically reduced energy-consumption growth. Our attitude to the growth of energy consumption will determine whether we will follow another dangerous exponential curve B or a more sensible growth pattern, such as that indicated by curve C.

2.9 SUPPLY VERSUS EFFICIENCY

The laws of exponential growth make it quite clear that we can match energy production with demand only if we limit the growth of demand. In addition, it turns out that efficiency (conservation) is more attractive than increasing the supply from both an economic and an environmental point of view. The Harvard Business School published a major report called *Energy Future* (Stobaugh and Yerkin, 1979), which clearly presented the economic advantages of efficiency. The report concluded that conservation combined with the use of solar energy is the best solution to our energy problem. All the years since this report was published have shown that it was right on target.

The economic advantage of efficiency is demonstrated by the following example. The Tennessee Valley Authority (TVA) was faced with an impending shortage of electrical energy required for the economic growth of the valley. The first inclination was to build new electric generating plants. Instead, a creative analysis showed that efficiency would be significantly less expensive. The TVA loaned its customers the money required to insulate their homes. Although the customers had to repay the loans, their monthly bills were lower than before, because the reduced energy bills more than compensated for the increase due to loan repayments. As a consequence of reduced consumption due to efficiency, the TVA had surplus low-cost electricity to sell, the customers paid less to keep their homes warm, and everyone had a better environment because no new power plants had to be built.

Efficiency is a strategy where everyone wins. And as Amory Lovins, a hero of the planet, says, "If a building is not efficient, it is not beautiful."

2.10 SUSTAINABLE-DESIGN ISSUES

Creating a sustainable green building involves all aspects of design, which is more than one book can discuss in detail. There is, however, an important subset of issues that is discussed here, namely, energy (see Fig. 1.9).

Heating, cooling, and lighting are all accomplished by moving energy into or out of a building. As mentioned in the previous chapter, buildings use about 48 percent of all the energy consumed in the United States. Because of global warming and air pollution, the energy subset of all the sustainability issues is the most urgent to address.

The highly regarded *Environmental Building News* printed a list of what it believes are the eleven most important sustainable design issues. They are reproduced below. Note that the first issue is "Save Energy: Design and build energy-efficient buildings." Although this book covers only some of the issues, the whole list is reproduced.

Priority List for Sustainable Building*

1. Save Energy: Design and build energy-efficient buildings.
2. Recycle Buildings: Utilize existing buildings and infrastructure instead of developing open space.
3. Create Community: Design communities to reduce dependence on automobiles and to foster a sense of community.
4. Reduce Material Use: Optimize design to make use of smaller spaces and utilize materials efficiently.
5. Protect and Enhance the Site: Preserve or restore local ecosystems and biodiversity.
6. Select Low-Impact Materials: Specify low-environmental-impact, resource-efficient materials.
7. Maximize Longevity: Design for durability and adaptability.
8. Save Water: Design buildings and landscapes that are water-efficient.
9. Make the Buildings Healthy: Provide a safe and comfortable indoor environment.
10. Minimize Construction and Demolition Waste: Return, reuse, and recycle job-site waste, and practice environmentalism in your business.
11. "Green Up" Your Business: Minimize the environmental impact of your own business practices, and spread the word.

Note that only item number five does not have a direct impact on energy consumption in buildings. The design and location of a building determines the amount of energy needed for its operation, its embodied energy, the energy it takes to supply water, and the energy needed to commute.

Reducing energy consumption is 90 percent of sustainability!

2.11 CLIMATE CHANGE

Energy issues are directly related to global warming. That latest report (2013) of the Intergovernmental Panel on Climate Change (IPCC) is clearer than ever that the warming of the climate is unequivocal and most of it is caused by human-created greenhouse gases. It also states that before the end of this century (1) the earth's temperature will rise; (2) there will be more and greater droughts, heat waves, cyclones, and heavy rainfall; and (3) sea levels will rise. In 2010, the National Research Council (a branch of the US National Academies of Science) suggested that by the end of the twenty-first century, temperatures will rise 4°F to 11°F (2.2°C to 6.1°C) and the oceans will rise 22 to 79 in. (0.55 to 2 m). Such predictions assume that the present trends continue, but that is not certain. In 2013, the National Research Council warned again that the climate can tip and that it could happen very soon.

The cause of the global warming is no mystery when we note the corresponding increase of the greenhouse gas carbon dioxide (Fig. 2.11a). Humanity is also heating the planet by producing methane, nitrous oxide, chlorofluorocarbons, and some other minor greenhouse gases. Most of the heating, however, is due to the carbon dioxide produced from burning the fossil fuels coal, oil, and natural gas. The greenhouse effect will be explained in the next section.

Even small increases in global temperatures can have serious effects besides deadly hotter summers. Precipitation patterns will change, with a corresponding disruption in agriculture; some of the world's poorest and most heavily populated regions will be losers. There will be more droughts in some areas and floods in others. Diseases that thrive in warmer climates, such as malaria, will spread over more of the globe, and species extinction will have a further negative impact on the present ecology. And perhaps most important, there will be a rise in the sea level.

Although the high prediction of 79 in. (200 cm) by the National Research Council is bad enough, sea levels could rise much more than that, especially if the climate suddenly tipped. It is worth asking what the maximum sea-level rise could be if all the ice on Greenland and Antarctica melted, which is possible because it has happened several times in geologic time. The seas could rise as much as 240 ft (80 m). Even if only 20 percent of the ice melted, the seas would rise 48 ft (14.4 m).

When important decisions are made about the future, we must base them not only on likelihood but also on the severity of outcomes. For example, few people play Russian roulette, where a person spins the cylinder of a revolver loaded with only one bullet, aims the muzzle at his head, and pulls the trigger (Fig. 2.11b). Although the probability of dying is only a low one in six (17 percent), sane people don't play because the outcome is a disaster.

*Reprinted by permission from the *Environmental Building News*. See the September–October 1995 issue for a more thorough discussion of these issues, which are as relevant today as they were in 1995.

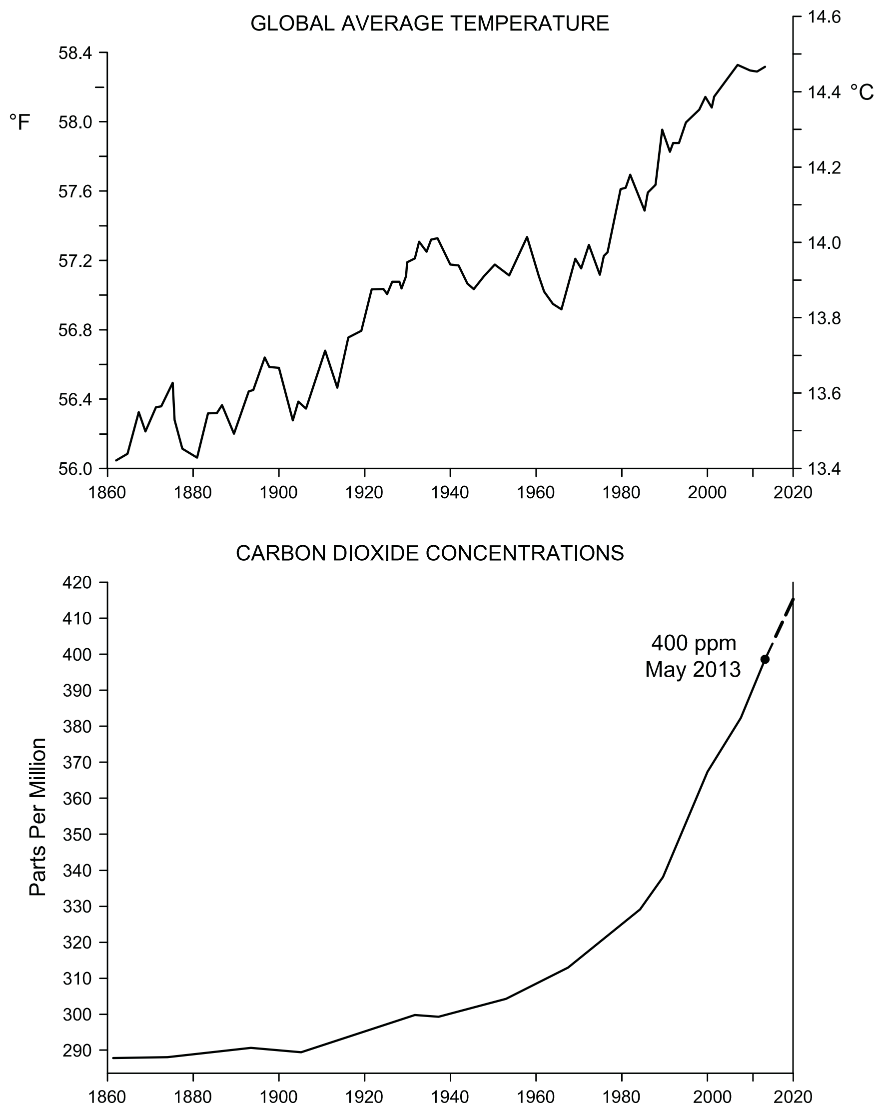


Figure 2.11a The upper graph represents the increase of the global average temperature, and the lower graph represents the increase of carbon dioxide during the same time period. (Sources: temperature data from Goddard Institute for Space Studies; carbon dioxide data from Scripps Institution of Oceanography, updated 2013.)

Similarly, we should not play Russian roulette with the planet, which we are clearly doing (Fig. 2.11c).

The fundamental and generally accepted "prudence principle" states: even if the probability is low, if the consequences are serious, then action should be taken. Thus, no matter what the probability of a global warming catastrophe, its seriousness requires us to take immediate action.

A major reason for the uncertainty of the of climate change is that the climate may suddenly tip like a tower that is leaning too far (Fig. 2.11d and e). We know of several phenomena that can cause the climate to tip, with the most obvious one being the changing solar reflectivity as ice melts in the Arctic and Antarctic. Snow and ice are about 90 percent reflective while land and open water are only 10 percent reflective. Thus, as more land and water are exposed, more sunlight is absorbed, increasing the temperature to melt more snow and ice—thereby exposing more land and water and a positive feedback loop is created.

A second known mechanism that can cause the climate to tip is the melting of the permafrost found in northern Canada, Europe, Russia, and Alaska. Huge amounts of organic material will decompose, giving off both carbon dioxide and methane, which is twenty-one times more powerful a greenhouse gas than carbon dioxide. Thus, a faster warming planet melts permafrost faster, which creates more greenhouse gases, and so on.

Another known tipping mechanism is the release of methane from a material called methane hydrate, also known as fire ice or flaming ice, because it consists of methane (natural gas) trapped within a crystal structure of water. A piece of methane hydrate, which looks like ice, will actually burn as the methane is released from the melting ice. Huge quantities of this material are found under sediments in oceans and lakes located in cold regions such as Siberia and northern Canada. Lakes in those cold regions can be set on fire in the summer as warm temperatures release the methane that then bubbles to the surface. Methane hydrates can also be found in permafrost. As the earth warms, methane will be released from the methane hydrate causing more warming releasing more methane—and so another positive feedback loop is created. Consequently, there are at least three vicious feedback cycles that can cause the climate to tip.

We must heed the warnings of Hurricanes Katrina and Sandy, super typhoons in Asia, major planetary heat waves, and unusual worldwide flooding by taking action immediately to minimize the severity of global warming. As the eminent physicist Albert A. Bartlett said, "We must recognize that it is not acceptable to base our national [planetary] future on the motto, 'When in doubt, gamble'" (Bartlett, 1978).

One of the main reasons for inaction is the mistaken belief that fighting global warming hurts the economy. The opposite is true. A major report in 2006 for the United Kingdom by Sir Nicholas Stern, a former chief economist with the World Bank, states that unless we

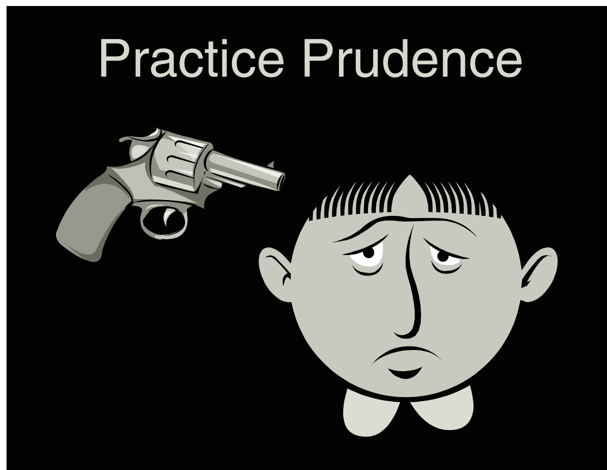


Figure 2.11b Russian roulette is unpopular not because of the odds but because the stakes are too high.



Figure 2.11c This generation has no right to play Russian roulette with the planet. It is immoral!



Figure 2.11d Many phenomena exhibit a tipping effect whereby change is gradual until a point of instability occurs. Global warming could well be such a phenomenon.

act soon, global warming will cause a worldwide economic depression. Furthermore, countries like Germany, which have made sustainability a national goal, are thriving economically.

Because of our tremendous appetite for energy, Americans produce more carbon dioxide per person than just about any other nation. Furthermore, because we have a long history of industrialization and because we have a large population, the United States has produced slightly under 30 percent of all the carbon dioxide in the atmosphere, which is by far the largest amount of any country (see Table 2.11). The recent abundance of oil and gas from fracking is a mixed blessing for the United States. It decreases our dependence on foreign energy sources,

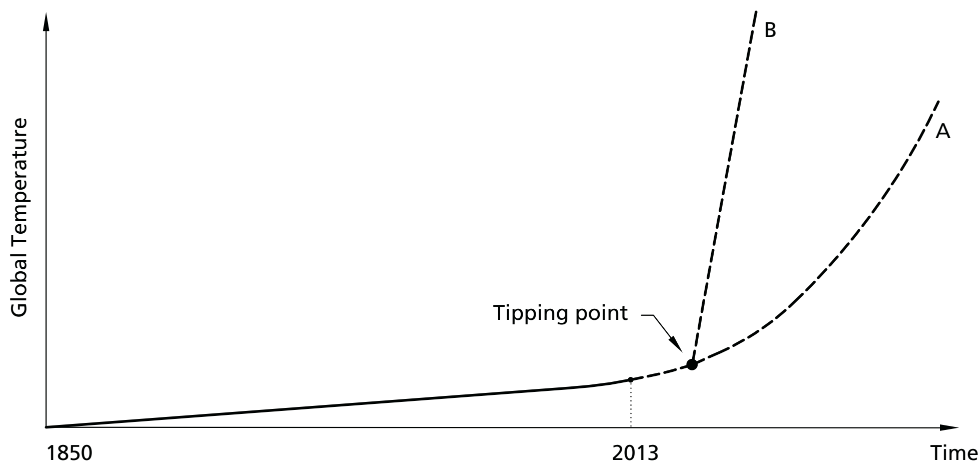


Figure 2.11e If or when the climate tips, changes to the environment would be very rapid rather than the more gradual changes we see today. A tipping climate greatly reduces the time available for taking corrective action.

Table 2.11 Contribution to Atmospheric Carbon Dioxide, by Country

Country	Percentage of World Total
United States	29.3
Russia	8.1
China	7.8
Germany	7.3
United Kingdom	6.3
Japan	4.1
France	2.9
India	2.2
Australia	1.1
Mexico	1.0
South Korea	0.8
Iran	0.6
Indonesia	0.5
Pakistan	0.2
Developed countries	76
Developing countries	24

Source: World Resource Institute

and the expanded use of natural gas is reducing our reliance on the most harmful fossil fuel, coal. Although natural gas is better than coal, it still adds significant amounts of carbon to the atmosphere, and its abundance and low cost delays our transfer to clean renewable fuels and takes the pressure off to make buildings more energy efficient.

2.12 THE GLOBAL GREENHOUSE

The greenhouse gases in the atmosphere act as a one-way radiation trap. They allow most of the solar radiation to pass through to reach the earth's surface, which then radiates increased amounts of heat back toward space in the form of long-wave infrared radiation, but the greenhouse gases trap some of this radiation (Fig. 2.12). Consequently, the earth warms up.

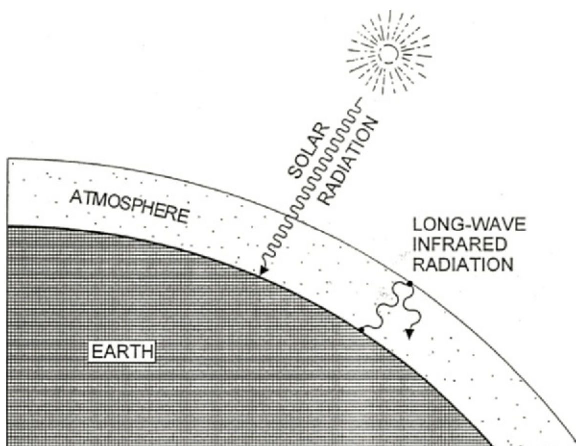


Figure 2.12 The atmosphere acts like a greenhouse by allowing most of the solar radiation to enter but blocking the long-wave infrared radiation from leaving the planet.

The present average global temperature is a consequence of the existing level of water vapor and other greenhouse gases mentioned above. The earth is about 60°F (35°C) warmer than it would be without these gases. When more greenhouse gases are added to the atmosphere, the equilibrium temperature increases and the earth gets warmer. The greenhouse effect is explained in more detail in Sections 3.10 and 3.11.

2.13 THE OZONE HOLE

The ozone hole is another example of a critical undesired change to the atmosphere. The air-conditioning of buildings has led indirectly to a hole in the ozone layer that protects the earth from most of the sun's harmful ultraviolet radiation (Fig. 2.13). The chlorofluorocarbon (CFC) molecules that were invented to provide a safe, inert refrigerant for air conditioners have turned out to have a tragic flaw, inertness, which ironically was considered their major virtue. When these molecules escape from air conditioners or are released as propellants in spray cans, they survive and slowly migrate to the upper atmosphere, which contains ozone. There, the CFCs deplete the protective ozone layer for an estimated fifty years before they themselves are destroyed. Consequently, the problems will be with us long after we eliminate all CFCs on the surface.

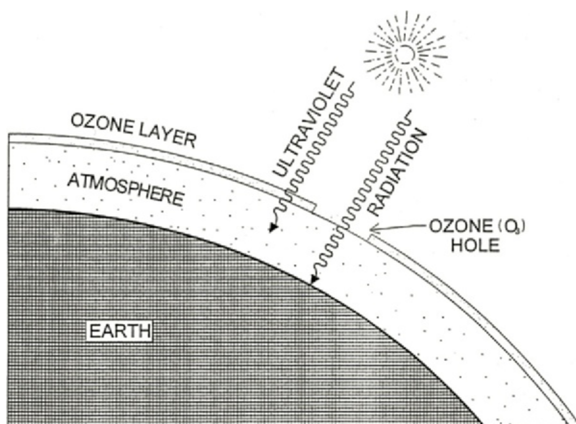


Figure 2.13 The depletion of the ozone layer allows greater amounts of the sun's harmful ultraviolet radiation to reach the earth's surface.

The 1987 Montreal Protocol, which the United States wholeheartedly supports, requires countries to phase out the production of CFCs. Although this is a classic example of how technological solutions can be the source of new problems, it is also a good example of how world cooperation based on sound science can respond quickly to a serious problem.

Regretfully, international cooperation has not succeeded as well in controlling greenhouse emissions. Progress is slow for various reasons, one of which is the shortsighted policies of some fossil-fuel and transportation industries.

2.14 EFFICIENCY VERSUS RENEWABLE ENERGY

When people discover that the consumption of fossil fuels is causing global warming, they commonly conclude that we should switch to clean, renewable energy from the sun, wind, or other sources. A less common reaction is the belief that we can greatly reduce the consumption of fossil fuels by reducing waste. Of course, we need to do both, but it must be clearly understood that by far the most important option is efficiency, since it is the easiest, quickest, and least expensive way to fight global warming. Efficiency is the low-hanging fruit (Fig. 2.14).

For example, optimized window design can reduce energy consumption and carbon dioxide production up to 40 percent. Although such a window system will cost more initially, it will not only reduce energy costs for the life of the building but will also reduce the first cost of the air-conditioning system thereby partially offsetting the cost of the windows.

Because most of this book discusses how to design energy efficient and solar responsive buildings, the remainder of this chapter discusses the various energy sources that are presently available mostly off-site to power buildings.



Figure 2.14 Efficiency is the low-hanging fruit. We should not put all our effort in going after the high fruits (photovoltaics, wind, hydrogen, etc.) until we have picked the low-hanging fruit (orientation, insulation, shading, etc.).

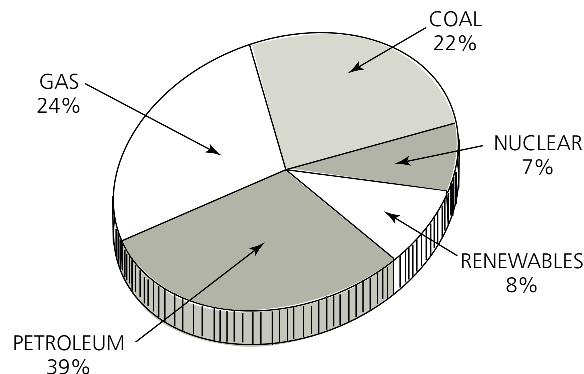


Figure 2.15 Energy consumption by source in the United States. Note that 92 percent is from nonrenewable sources.

2.15 ENERGY SOURCES

Which energy sources are available to power buildings, and which of these are sustainable? We can divide all of the sources into the two main categories: renewable and nonrenewable:

- I. Renewable
  - A. Solar
  - B. Wind
  - C. Biomass
  - D. Hydroelectric
  - E. Geothermal
- II. Nonrenewable
  - A. Fossil fuels
    1. Oil
    2. Natural gas
    3. Coal
  - B. Nuclear
    1. Fission
    2. Fusion?

Figure 2.15 shows that we are using mostly nonrenewable energy sources. This is an unfortunate situation because not only are we using up these sources, but they are the very ones causing pollution and global warming. We must switch as quickly as possible from nonrenewable to renewable sources. Before we look at each source in terms of its ability to power buildings sustainably, let's look at a brief example of the history of energy use in buildings.

2.16 ENERGY USE IN ANCIENT GREECE

The role of energy in buildings was largely ignored in recent history until the energy crisis of 1973, when some of the leading members of the Organization of Petroleum Exporting

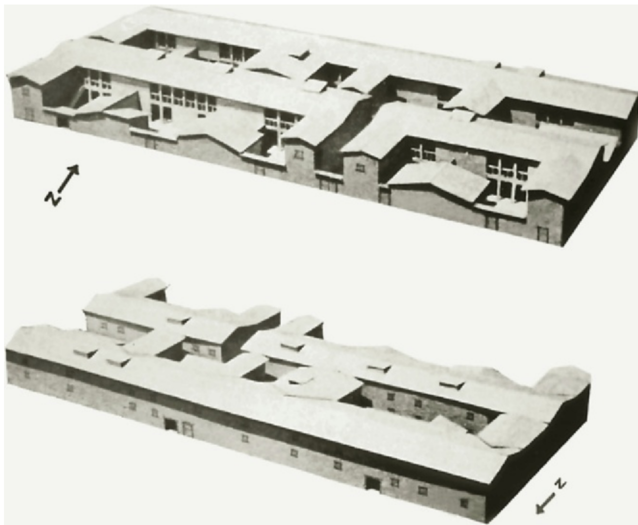


Figure 2.16 Solar buildings were considered modern in ancient Greece. Olynthian apartments faced south to capture the winter sun. Note that there are no east or west windows and only a few and small northern windows. (From *Excavations at Olynthus, Part 8: The Hellenic House*. © Johns Hopkins University Press, 1938).

Countries (OPEC) suddenly raised prices and set up an embargo on oil exports to the United States. The resulting energy shortages made us realize how dependent we were (and still are) on unreliable energy sources. We began thinking about how we use energy in buildings.

Before the energy crisis, a discussion of ancient Greek architecture would not have even mentioned the word "energy." The ancient Greeks, however, became aware of energy issues as the beautiful, rugged land on which they built their monuments became scarred and eroded by the clearing of trees to heat their buildings. The philosopher Plato said of his country: "All the richer and softer parts have fallen away and the mere skeleton of the land remains."

The ancient Greeks responded to their energy crisis partly by using solar energy. The philosopher Socrates thought that this was important enough to compel him to explain this method of designing buildings. According to the historian Xenophon, Socrates said: "In houses that look toward the south, the sun penetrates the portico in winter, while in summer the path of the sun is right over our heads and above the roof so that there is shade" (see Fig. 2.16). Socrates continued talking about a house that has a two-story section: "The section of the house facing south must be built lower than the northern section in order not to cut off the winter sun" (Butti and Perlin, 1980).

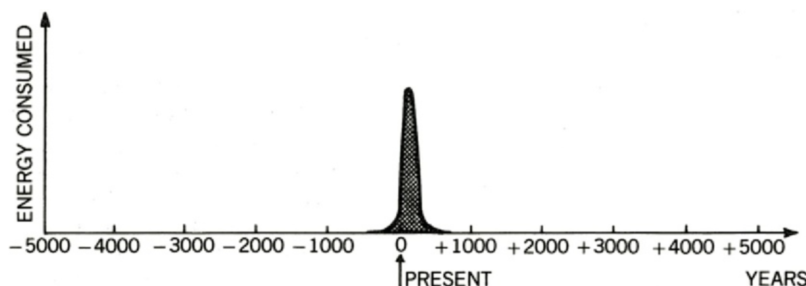


Figure 2.17a The age of fossil fuels in the longer span of human history. (After Hubbert.)

2.17 NONRENEWABLE ENERGY SOURCES

When we use nonrenewable energy sources, we are much like the heir living it up on an inheritance with no thought of tomorrow until one day he or she finds that the bank account is empty. Two major categories of nonrenewable energy sources exist: fossil fuels and nuclear energy.

Fossil Fuels

For hundreds of millions of years, green plants trapped solar energy by the process of photosynthesis. The accumulation and transformation of these plants into solid, liquid, and gaseous states produced what we call the fossil fuels: coal, oil, and natural gas. When we burn these, we are actually using the solar energy that was stored hundreds of millions of years ago. Because of the extremely long time required to convert living plants into fossil fuels, in effect they are depletable or nonrenewable energy sources. The fossil-fuel age started around 1850 and will last at most a few centuries more. The finite nature of the fossil-fuel age is clearly illustrated by Figure 2.17a.

Most air pollution and smog are a result of the burning of fossil fuels (see Fig. 2.17b). The use of fossil fuels also causes acid rain, mercury poisoning, and most important of all, global warming.

Natural Gas

Natural gas, which is composed primarily of methane, is a convenient source of energy. Except for the global-warming carbon dioxide it produces when burnt, it is a clean energy source. With the extensive pipeline system that exists, natural gas can be delivered to most of the populated areas of the United States and Europe. Once burnt



Figure 2.17b Air pollution covering New York City is not like this every day. Often the pollution is blown away to Connecticut or New Jersey.



Figure 2.17c Oil platforms for drilling underwater are very expensive, making the extracted oil also more expensive.

at the oil well as a waste by-product, it is in great demand today. Natural gas is again bountiful because of the recently developed "fracking" techniques of extracting gas from shale. As stated above, this new source of natural gas is a mixed blessing. On the plus side is its displacement of coal, but on the negative side, fracking causes ground and water pollution and may cause accidental release of significant amounts of methane, which is twenty-one times more powerful a greenhouse gas than carbon dioxide.

Oil

The most useful and important energy source today is oil. But the world supply is limited and will be mostly depleted by the end of this century. Unconventional sources of oil such as fracking and tar sands are creating a temporary reprieve in the rising cost of oil. Unfortunately, extracting oil by fracking and from tar sands not only pollutes land and water but also causes increased global warming, because more energy is needed in the extraction. A gallon of gasoline from these sources causes much more global warming than a gallon derived by more conventional methods.

Since much of the easily obtainable oil has already been pumped out of the round, we are now forced to use fracking, much deeper wells, deep sea wells (Fig. 2.17c), and go to almost inaccessible places, such as the north slope of Alaska. Difficult places to drill also increases the chances of serious oil spills like the BP Deepwater Horizon oil spill in the Gulf of Mexico in 2010.

Most important, however, is that no matter where the oil comes from, burning it produces carbon dioxide and thereby global warming.

Coal

By far the most abundant fossil fuel we have is coal, but significant problems are associated with its use. The difficulties start with the mining. Deep mining is dangerous to miners in two ways. First, there is the ever-present danger of explosions and mine cave-ins. Second, in the long run there is the danger of severe respiratory ailments due to the coal dust. If the coal is close to the surface, strip mining might be preferred. Although strip mining is less dangerous to people, it is quite harmful to the land. Reclamation is possible but expensive. Much of the strip mining occurs in the western United States, where the water necessary for reclamation is a scarce resource.

Additional difficulties result because coal is not convenient to transport, handle, or use. Since coal is a rather dirty fuel to burn and a major cause of acid rain and mercury in the environment, its use will likely be restricted to large burners, where expensive equipment can be installed to reduce air pollution. Even if coal is burned "cleanly," it still produces huge amounts of carbon dioxide and thereby much global warming.

To overcome some of the negative impacts, the coal industry has developed a technology called clean coal, and it has suggested that carbon dioxide emissions from power plants could be sequestered. However, using clean coal technology raises costs, and carbon-dioxide sequestering will raise costs even further to the point where coal will not be cost competitive.

All of these difficulties add up to coal being inconvenient, expensive,

risky, and a major cause of global warming. Although plentiful, it is not the answer to our energy problems.

Nuclear Fission

In fission, certain heavy atoms, such as uranium-235, are split into two middle-size atoms, and in the process give off neutrons and an incredible amount of energy (Fig. 2.17d). During the 1950s, it was widely believed that electricity produced from nuclear energy would be too cheap to meter.

Even with huge governmental subsidies because of nuclear energy's defense potential, this dream has not become a reality. In fact, just the opposite has happened. Nuclear energy has become one of the most expensive and least desirable ways to produce electricity. One important factor in the decline of nuclear power is that the public is now hesitant to accept the risks. Nuclear power accidents, such as the ones that took place at Chernobyl in the Soviet Union in 1986 and Fukushima in Japan in 2011, spread deadly radiation over large areas. The nuclear accident at Three Mile Island, Pennsylvania, in 1979 might have been just as serious if a very expensive containment vessel had not been built. More than twenty years later, the reactor is still entombed, with a billion-dollar cleanup bill. The safety features needed to prevent accidents or minimize their impact have made the plants uneconomical. Even with all the safety features, the risks are still not zero, as Figure 2.17e shows.

The overall efficiency of nuclear power plants has not been as high as had been hoped. The initial cost of a nuclear power plant is high, the operating efficiency is low, and the problem of disposing of radioactive nuclear waste has still not been solved.

Since uranium is a rare element, unearthing it requires huge mines that create mountains of radioactive waste. Nuclear power plants also need huge amounts of cooling water. Plants that are located on rivers either

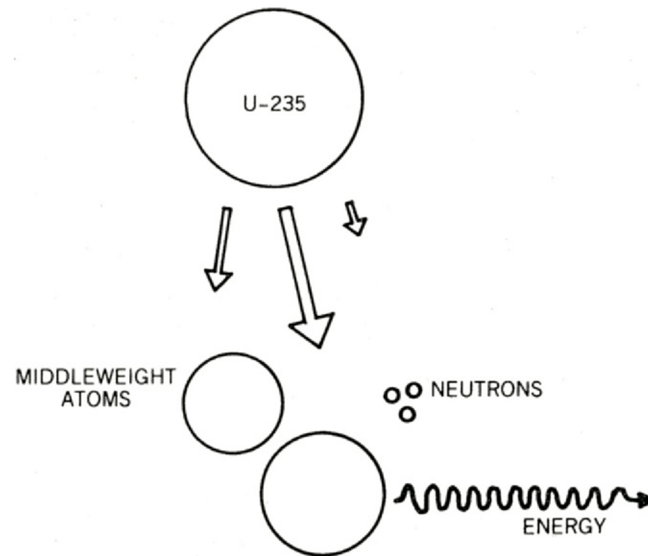


Figure 2.17d Nuclear fission is the splitting apart of a heavy atom.



Figure 2.17e Take this quiz: This sign refers to what kind of power plant? (A) photovoltaic, (B) wind, (C) biomass, (D) nuclear. (Courtesy of Southern Nuclear).

use or heat up the river. In 2003, during a heat wave and drought, France had to shut down some of its nuclear power plants because they were overheating the rivers that cooled them.

Lately, the nuclear power industry has argued that new technology is foolproof, yet they want the government to pass a law exempting them from all liability. Why is that necessary if their new systems are foolproof?

Thus, there are many excellent reasons not to go with the nuclear option besides the fact that it is much more expensive than renewable energy. As the business magazine the *Economist* said in its May 19, 2001, issue: "Nuclear power, once claimed to be too cheap to meter, is now too costly to matter." Although nuclear energy does not produce greenhouse gases, there are more economical options to displacing fossil fuels.

Nuclear Fusion

When two light atoms fuse to create a heavier atom, a process called fusion, energy is released (Fig. 2.17f). This is the same process that occurs in the sun and other stars. It is quite unlike fission, a process through which atoms decay by coming apart.

Fusion has many potential advantages over fission. Fusion uses hydrogen, the most plentiful material in the universe, as its fuel. It produces much less radioactive waste than fission. It is also an inherently much safer process because fusion is self-extinguishing when something goes wrong, while fission is self-exciting.

All the advantages, however, do not change the fact that a fusion power plant does not yet exist, and we have no guarantee that we can ever make fusion work economically. Even the greatest optimists do not expect fusion to supply significant amounts of power anytime soon.

Considering the shortcomings, perhaps the best nuclear power plant is the one 93 million mi (150 million km) away: the sun. It is ready to supply us with all the energy we need right now.

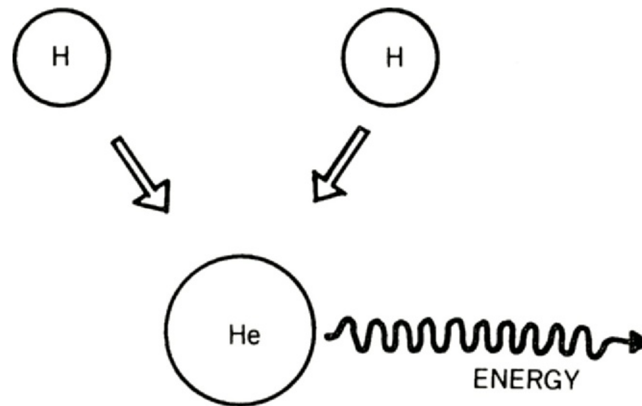


Figure 2.17f Nuclear fusion consists of the union of very light atoms. For example, the fusion of two hydrogen atoms yields an atom of helium as well as a great deal of extra energy.

2.18 RENEWABLE ENERGY SOURCES

The following sources all share the very important assets of being renewable and of not contributing to global warming. Solar, wind, hydroelectric, and biomass are renewable because they are all variations of solar energy. Of the renewable energy sources, only geothermal energy does not depend on the sun.

Solar Energy

The term "solar energy" refers to the use of solar radiation in a number of different ways. The building-integrated solar collection methods are all discussed at some depth in this book:

- Passive solar energy (Chapter 7)
- Photovoltaics and active solar energy (Chapter 8)
- Daylighting (Chapter 13)

The phrase "solar energy" is also used to describe large centralized systems that produce electricity either with solar electric systems (photovoltaics) or solar thermal systems that generate steam to power electric generators.

In one year, the amount of solar energy that reaches the surface of the earth is 10,000 times greater than all the energy of all kinds that humanity uses in that period. Why, then, aren't we using solar energy? This question can be explained only partly by the technical problems involved. These technical problems stem from the diffuseness, intermittent availability, and uneven distribution of solar energy. However, these problems are being resolved.

The main nontechnical challenge for solar energy is that most people equate it with photovoltaics (PV) usually called solar panels. When they discover that PV is expensive, they conclude that solar is expensive. Nothing is further from the truth. Figure 2.18a shows the solar-responsive design tree with the height of different fruits representing different solar strategies. Since "pick the low-hanging fruit first" is a wise policy, solar strategies such as building orientation, building color, and window distribution should be utilized first. These lowest-hanging solar strategies save huge amounts of energy and are free. The next higher ones are not free but are very cost-effective.

Solar energy consists of more than just photovoltaics (PV)!

Other nontechnical problems facing the acceptance of solar energy are primarily a result of people's beliefs that it is unconventional, looks bad, does not work, is futuristic, etc. On

the contrary, in most applications, such as daylighting or the use of sunspaces, solar energy adds special delight to architecture. Interesting aesthetic forms are a natural product of solar design (see Fig. 11.6e and 11.6f). Solar energy promises to not only increase the nation's energy supply and reduce global warming but also enrich its architecture.

Besides being renewable, solar energy has other important advantages. It is exceedingly kind to the environment. No air, water, land, or thermal pollution results. Solar energy is also very safe to use. It is a decentralized source of energy available to everyone everywhere. With its use, individuals are less dependent on brittle or monopolistic centralized energy sources, and countries are secure from energy embargoes. China, Germany, Japan, and Switzerland have embarked on ambitious solar programs in order to become more energy-independent, while in the United States solar is underutilized.

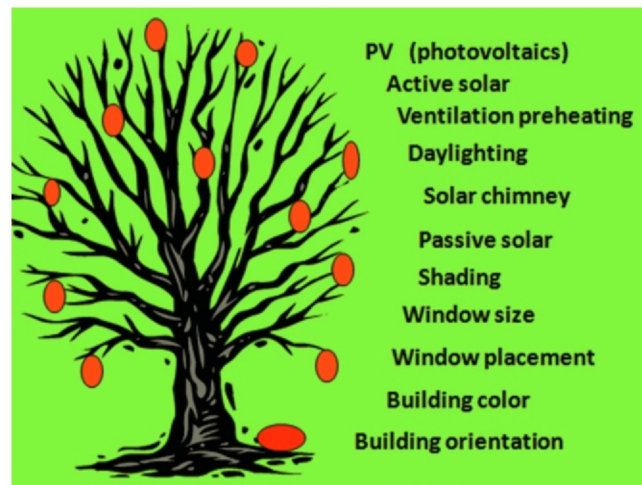


Figure 2.18a The solar-responsive design tree not only shows all of the existing solar strategies but also the order in which they should be picked (i.e. the lowest-hanging fruit first).

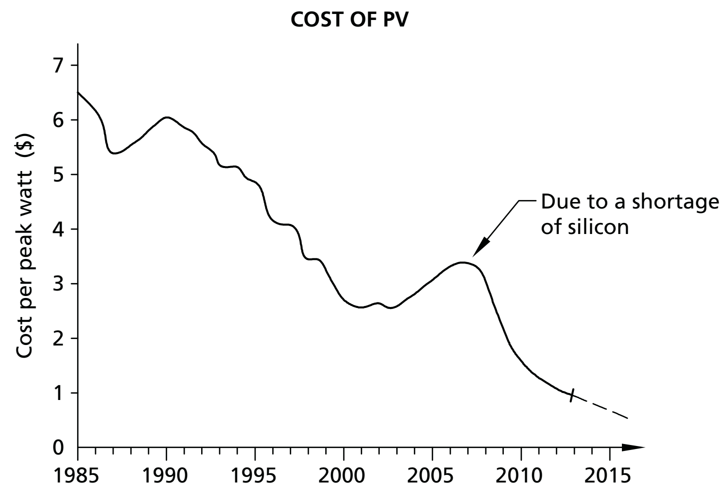


Figure 2.18b The cost of PV electricity has declined dramatically and will almost certainly continue to decline. Nevertheless, PV is more expensive than other solar strategies, especially the free ones.

Photovoltaic Energy

If one were to imagine the ideal energy source, it might well be photovoltaic (PV) cells. They are often made of the most common material on earth: silicon. They produce the most flexible and valuable form of energy: electricity. They are very reliable—no moving parts. They do not pollute in any way—no noise, no smoke, no radiation. And they draw on an inexhaustible source of energy: the sun.

Over the last thirty years, the cost of PV electricity has been declining steadily, and it is in the process of becoming competitive with conventional electricity (Fig. 2.18b). PV electricity is already competitive for installations that are far from the existing power grid, and during peak demand times when electricity is very expensive.

The greatest potential may lie with building-integrated photovoltaics (BIPV) both for our energy future and for architecture. For more information about PV see Chapter 8.

Wind Energy

The ancient Persians used wind power to pump water. Windmills first came to Europe in the twelfth century for grinding wheat and pumping water. More than six million windmills and wind turbines have been used in the United States over the last 150 years partly to grind wheat but mostly to pump water on farms and ranches (Fig. 2.18c and d). Wind turbines also produced electricity for some remote areas before rural electrification in the 1930s.

Today, wind turbines are having a major revival because they can produce clean, renewable energy at the same cost as conventional energy. Where wind is plentiful and electricity is expensive, wind power is often the least expensive source of electricity. All over the world, giant wind turbines and wind farms are generating electricity for the power grid, and wind



Figure 2.18c This windmill in Colonial Williamsburg, Virginia, was used to grind wheat.



Figure 2.18e Utility-size wind farms like this one in Oklahoma are being built all over the world.



Figure 2.18d Windmills still pump water on some ranches and farms, and small modern wind turbines produce electricity for individual homes.

electricity could supply all U.S. energy needs (Fig. 2.18e).

Small wind turbines can be a source of electricity for individual buildings where the wind resource is sufficient, which is a function of both velocity and duration. Color plate 20 shows where favorable wind conditions can be found in the United States. Of course, local conditions are critical, and a local survey should be made. Mountaintops, mountain passes, and shorelines are often good locations in all parts of the country. For economic reasons, minimum annual average wind speeds of 9 mph (14 kph), or 4 meters per second (m/s), are needed. See the end of the chapter for information on wind-resource availability.

Both theory and practice have shown that wind turbines are not appropriate for urban areas because turbines require smooth airflow, and buildings create much turbulence. Furthermore, vibration and noise make wind turbines inappropriate even for isolated, very tall buildings.

Since the power output of a wind turbine is proportional to the cube of the wind speed (see Sidebox 2.18), a windy site is critical, and there is a great incentive to raise the turbine as high into the air as possible to reach higher wind speeds. Most often, wind machines are supported on towers,

SIDEBOX 2.18

The power produced by a wind machine is proportional to the cube of the wind speed and the square of the rotor radius,

$$P \approx v^3 \times d^2$$

Where

P = power output
v = air speed
d = rotor diameter

For example, the power output will be 8 (2^3) times as large if the wind speed doubles. Stated another way, a 12.6 mph (20 kph) wind will yield twice the power of a 10 mph (16 kph) wind.

Also, if the rotor diameter is doubled (2^2), the power output will be four times as large.

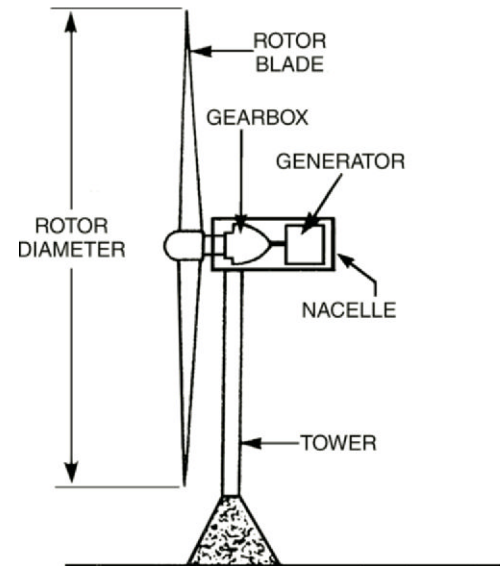


Figure 2.18f The essential components of a wind turbine are shown. (Drawing from DOE/CE-0359P.)

some as high as 400 ft (125 m). Wind turbines come in all sizes, but even the small ones should be mounted at least 40 ft (12 m) above the ground in order to catch enough wind.

The power output of a wind turbine is also proportional to the square of the length of the rotor blades (Fig. 2.18f). A 6.6 ft (2 m) diameter rotor is enough to power a television, while a 66 ft (20 m) diameter rotor can generate enough electricity for five hundred Americans or one thousand Europeans. Because larger is much better in the case of wind turbines, the largest today are 500 ft (150 m) in diameter and still larger ones are on the drawing boards.

The intermittent nature of wind power is not a serious problem, since other energy sources can supply the electricity to the grid when there is not enough wind. Although wind's intermittent nature must be accounted for, it is nevertheless one of the best renewable energy sources.

In stand-alone systems, a large battery is needed to supply electricity when the wind is not blowing. It has been found, however, that hybrid systems combining wind power with PV cells are very efficient because they complement each other. In winter, there is less sun but more wind, while in summer, the PV cells generate more electricity than the wind turbine. Similarly, on stormy days, there is less sun but more wind. Thus, wind turbines and PV cells are frequently used together, as shown in Figure 8.5c. Also see Sections 8.5 and 8.6 for a discussion of typical electrical systems.

Especially in certain locations, wind machines have killed some birds. Although this is a concern, it is a minor problem when compared with the approximately 57 million birds that are killed each year in collisions with cars and 97 million birds killed in collisions with plate-glass windows.

Although some wind farms are spread over large areas of land, the land can still be used for crops and grazing. This is not the case for hydropower, where the land behind the dam is flooded and lost. Also, wind farms require only about one-fifth the amount of land that hydropower needs.

There is also some concern about the aesthetic impact of wind farms because, by their very nature, wind machines must be high in the air. There have been few complaints about actual installations, and the author believes there is inherent beauty in a device that produces renewable, nonpolluting energy.

Biomass Energy

Photosynthesis stores solar energy for later use. This is how plants solve the problems of diffuseness and intermittent availability, which are associated with solar energy. This stored energy can be turned into heat or electricity, or converted into such fuels as methane gas, alcohol, and hydrogen. Because biomass is renewable and carbon neutral, and because with modern technology its use is relatively pollution-free, it is an attractive energy source. Two major sources of biomass exist: (1) plants grown specifically for their energy content and (2) organic waste from agriculture, industry, and consumers (garbage).

Some types of biomass can be converted into biofuels, while the rest is burned to create electricity. There are three major types of biofuels: (1) ethanol alcohol, (2) biodiesel, and (3) methane.

Because ethanol alcohol is presently made from sugars or carbohydrates, large-scale use will compete with food production, and on a worldwide basis there is no food to spare. Consequently, alcohol made from cellulose is a better source. Plants like switchgrass, which can grow on land too poor for food production, would be ideal sources of cellulose. Unfortunately, at this point, creating alcohol from cellulose is a process still being perfected.

Biodiesel can use oil wastes from restaurants, but when made from other plants it again competes with food or causes ecological damage. Thus, biodiesel is good but limited in its use.

Methane, the main component of natural gas, is an excellent biofuel when made from the decay of waste materials on farms, ranches, or landfills (Fig. 2.18g). Not only is it a valuable fuel, but its collection and combustion prevent its addition to the atmosphere, where it acts as a greenhouse gas twenty-one times more powerful than carbon dioxide.

We must be careful about turning biomass into energy, because decomposed biomass is food for new plants (Fig. 2.18h). As William McDonough, architect, author, and former dean of the School of Architecture at the University of Virginia, said, "Waste is food."

Burning biomass instead of fossil fuels can reduce the problem of global warming because biomass is carbon neutral. When growing, plants remove the same amount of carbon dioxide from the atmosphere that is returned when the biomass is burned. Thus, over time, there is no net change in the carbon-dioxide content of the atmosphere.

Wood used to heat houses is an example of biomass energy. Large-scale burning of wood in fireplaces or stoves, however, is not desirable because of the low efficiency and large amount of air pollution produced. Fireplaces are very inefficient (see Section 16.2), and wood stoves are better but still polluting.

Biomass is a desirable source of energy, but limited, for several reasons: it is needed to produce food and products such as lumber; it is advantageous to agriculture that it be returned to the ground to fertilize the next crop; and it provides a means to sequester carbon from the atmosphere, through creation of permanent topsoil (see Colorplate 22).

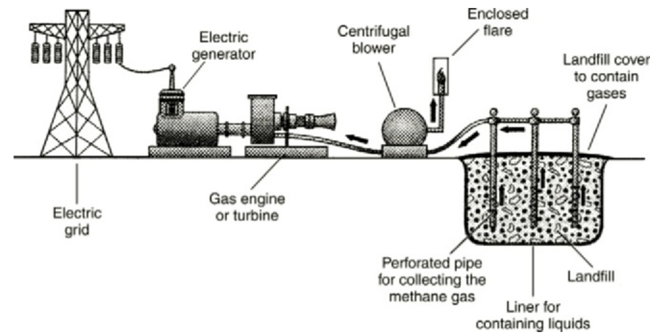


Figure 2.18g Landfill gas can be collected to generate electricity. (Fact Sheet No. 16, Texas State Energy Conservation Office.)



Figure 2.18h Saving biomass to replenish the soil makes sense at both the macro and micro level. This sign was found in a residential development outside of Houston, Texas.

Hydroelectric Energy

The use of water power, also called hydropower or hydroelectricity, has an ancient history: watermills were already popular in the Roman Empire. The overshot wheel (Fig. 2.18i) was found to be the most efficient, but it required at least a 10 ft (3 m) fall (head) of the water. When there was little vertical fall in the water but sufficient flow, an undershot wheel (Fig. 2.18j) was found to be best. Today, compact turbines are driven by water delivered in pipes.

The power available from a stream is a function of both head and flow. Head is the pressure developed by the vertical fall of the water, often expressed in pounds per square inch (kilopascals). Flow is the amount of water that passes a given point in a given time as, for example, ft^3 per minute (liters per second). The flow is the result of both the cross section and velocity of a stream or river.

Since power output is directly proportional to both head and flow, different combinations of head and flow will work equally well. For example, a very small hydropower plant can be designed to work equally with 20 ft of head and a flow of 100 ft^3 per minute (6 m and 48 l/s), or 40 ft of head and a flow of 50 ft^3 per minute (12 m and 24 l/s).

Today, water power is used almost exclusively to generate electricity. The main expense is often the dam that is required to generate the head and store water to maintain an even flow (Fig. 2.18k). One advantage of hydropower over some other renewable sources is the relative ease of storing energy. The main disadvantage of hydroelectricity is that large areas of land must be flooded to create the storage lakes. This land is most frequently prime agricultural land and is often highly populated. Another disadvantage is the disturbance of the local ecology as



Figure 2.18i An overshot waterwheel is best used where river water can be diverted high enough to be dropped onto the waterwheel. The waterwheel shown is in Korea.



Figure 2.18j Undershot waterwheels use the flow of the river for power. These Chinese waterwheels were used to lift river water for irrigation.



Figure 2.18k Hydroelectric dams produce pressure (head). Some also store water, and therefore energy, for later use.

when fish cannot reach their spawning grounds. For this reason, many existing dams in the United States are being demolished.

Figure 2.18l illustrates a simple, small-scale hydroelectric system. The dam generates the required head, stores water, and diverts water into the pipe leading to the turbine located at a lower elevation. Modern turbines have high rotational speeds (rpm) so that they can efficiently drive electric generators.

All but the smallest systems require dams, which are both expensive and environmentally questionable. Very small systems are known as "microhydropower" and can use the run of the river without a dam. The site must still have an elevation change of at least 3 ft (1 m) in order to generate the minimum head required. Of course, the more head (elevation change), the better.

About 5 percent of the energy in the United States is supplied by falling water. At present, we are using about one-third of the total hydroelectric resource available. Full use of this resource is not possible because some of the best sites remaining are too valuable to lose. For example, it would be hard to find anyone who would want to flood the Grand Canyon or Yosemite Valley behind hydroelectric dams. Most Americans now see our scenic rivers and valleys as great resources to be protected.

Hydroelectric energy will continue to be a reliable but limited source for our national energy needs.

Marine Energy

The four types of marine power sources are (1) tidal power, (2) wave

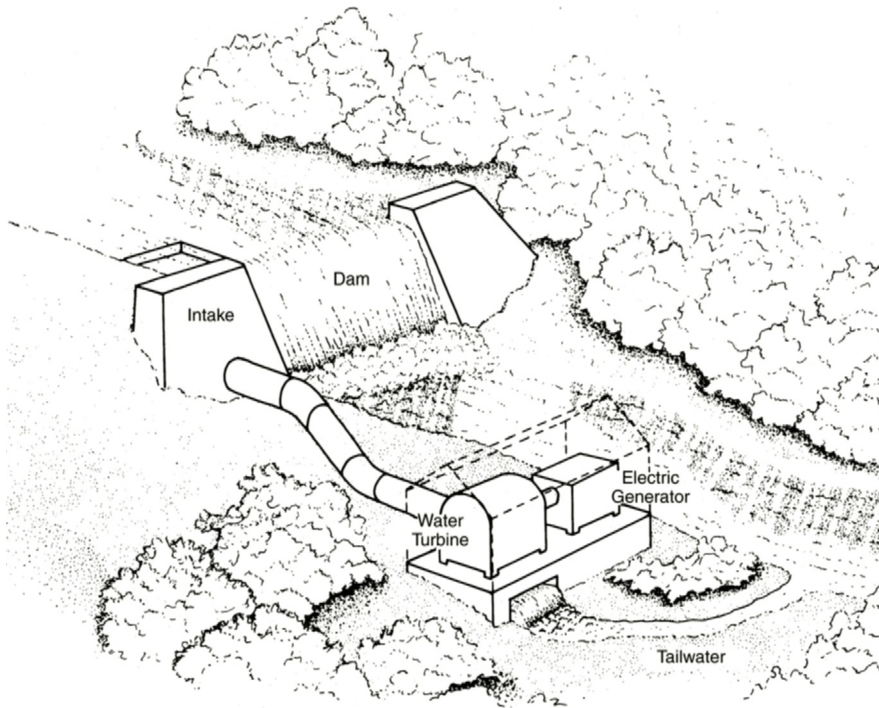


Figure 2.18l A simple, small-scale hydroelectric system. The dam can be eliminated with a run-of-river system in a fast-flowing stream or river by placing propeller-driven generators in the flow of water. (From *Building Control Systems* by Vaughn Bradshaw. 2nd edition. © John Wiley & Sons, Inc. 1993.)

power, (3) ocean-current power, and (4) ocean thermal-energy conversion.

Tidal power has been used for centuries with great success. Because it is most efficient where bays have small openings to the sea, its application is limited. Wave power is more widely distributed but more difficult to harness. Ocean-current power is very much like wind power except that water turbines are used. Like wind, it is available only in certain locations. Ocean thermal-energy conversion (OTEC) uses the large temperature difference between the deep ocean and its surface to generate power. All of the marine energy sources except tidal power are still in their experimental and development stages.

Geothermal Energy

The term "geothermal" has been used to describe two quite different energy systems: (1) the extraction of heat originating deep in the earth, and (2) the use of the ground just below the surface as a source of heat in the winter and a heat sink in the summer. To eliminate confusion, the second system is often called by the much more descriptive name "geo-exchange."

Geothermal energy is available where sufficient heat is brought near the surface by conduction, bulges of magma, or circulation of groundwater to great depths. In a few places, like Yellowstone National Park, hot water and steam bring the heat right to the surface. Other such sites, like the geysers in northern California and the Hatchobaru power station in Japan, use this heat to generate electricity. In some places like Iceland, geothermal energy is also used to heat buildings. Although surface sites are few in number, there is a tremendous resource of hot rock energy at depths of 5 to 10 mi (8 to 16 km). By drilling two holes, water can be pumped down one hole to the hot rock layers where it is heated, and then the hot water and/or steam can be returned through the second hole to drive a turbine or heat buildings. In the city of Boise, Idaho, a geothermal system heats over 360 buildings, including the state capitol. The United States has enough geothermal resources (Colorplate 23) to meet 6 percent of its 2025 energy needs.

Geo-Exchange

The low-grade thermal energy contained by the ground near the surface can be extracted by a heat pump to heat buildings or domestic hot water (heat pumps are explained in Section 16.10). This same heat pump can use the ground as a heat sink in the summer. Since the ground is warmer than the air in winter and cooler than the air in summer, a ground-source heat pump is much more efficient than normal air-source heat pumps. Also, since electricity is used to pump heat and not create it, a geo-exchange heat pump is three to four times more efficient than resistance electric heating.

The use of geo-exchange heat pumps can significantly reduce our consumption of energy and the corresponding emission of pollution and greenhouse gases. Reductions of 40 percent over air-source heat pumps and reductions of 70 percent compared to electric-resistance heating and standard air-conditioning equipment are feasible. See Section 16.11 for a more detailed discussion of this excellent system.

2.19 HYDROGEN

Although hydrogen is not a source of energy, it might play an important role in a sustainable economy. Hydrogen is the ideal nonpolluting fuel because when it is burned, only water is produced. It does not contribute to global warming.

Hydrogen is abundant, but all of it is locked up in compounds, such as water (H_2O). The closest place to mine free hydrogen is the planet Jupiter. Until we can go there, we will have to manufacture it here on earth. To produce free hydrogen, energy is needed to break the chemical bonds.

Although several methods exist for producing hydrogen, the process must use renewable energy sources if it is to produce a truly clean, sustainable fuel. Hydrogen can be separated from natural gas, coal, or other hydrocarbons by a process called reformation, but this source of hydrogen is not sustainable, since it still uses fossil fuels as the source of energy. Hydrogen can also be created by living organisms in ponds, but the most practical source is electrolysis using electricity generated by wind and PV. Hydrogen is a good match for the intermittent sources of solar and wind whose main weakness is energy storage. Whenever excess electricity is produced, it can be used to produce hydrogen from water by electrolysis (Fig. 2.19). The hydrogen can then be used to generate pollution-free electricity in fuel cells, which are explained in Section 3.22. It can also be used as a fuel to power automobile engines.

The efficient and economical storage of hydrogen remains a technical problem, however. The high-pressure tanks are heavy and expensive. To store hydrogen as a liquid is even more difficult because it then must be cooled to −423°F (−253°C). A more efficient solution might be to store the hydrogen in chemical compounds called **hydrides**. However, much more research is needed to make hydrogen the fuel of choice.

Hydrogen has the potential to become a clean, renewable fuel to power our cars and buildings, but since it is not a source of energy, we must still develop the renewable energy sources described above.

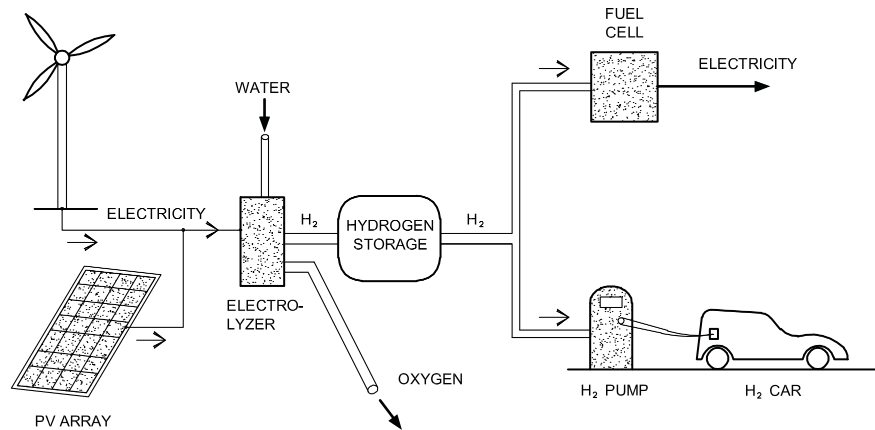


Figure 2.19 Hydrogen will be sustainable only if it is produced by renewable energy such as PV and wind. It can be used as both a fuel for our vehicles and for fuel cells that power and heat our buildings.

2.20 CONCLUSION

If we are looking for insurance against want and oppression, we will find it only in our neighbors' prosperity and goodwill and, beyond that, in the good health of our worldly places, our homelands. If we were sincerely looking for a place of safety, for real security and success, then we would begin to turn to our communities—and not the communities simply of our human neighbors, but also of the water, earth, and air, the plants and animals, all the creatures with whom our local life is shared.

—*Wendell Berry, Author*

We are not achieving safety by the way we use energy. We are damaging the environment, changing the climate, and using up our nonrenewable energy sources at a phenomenal rate. Our present course is not sustainable.

Since buildings use almost one-half of all the energy consumed and almost three-quarters of all the electricity, the building-design community has both the responsibility and the opportunity to make major changes in the way we use energy. The amount of energy a building consumes is mainly a function of its design.

Since the energy crisis of 1973, many fine buildings have shown us that buildings can be both energy efficient and aesthetically successful. As Bob Berkebile, one of our most environmentally responsive architects, has said, "If a building makes animals or people or the planet sick, it's not beautiful and it's not good design" (Wylie, 1994).

We in the United States have a special obligation because we use 25 percent of the world's energy and produce 22 percent of the carbon dioxide, but have only 5 percent of the world's population (Fig. 2.20a). As mentioned before, each American produces more

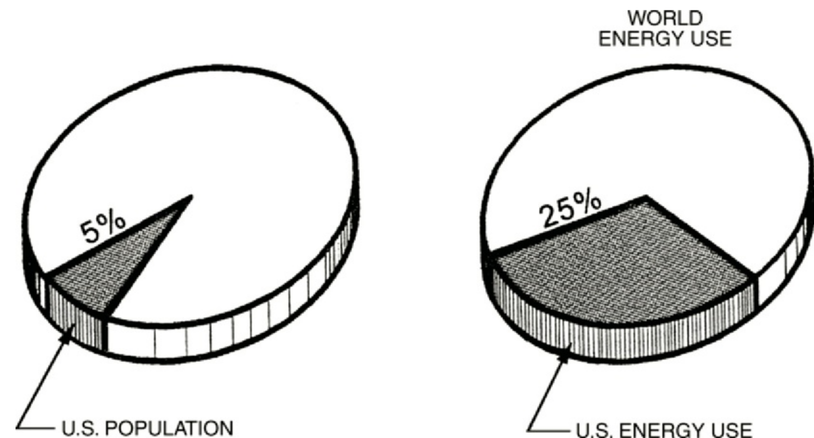


Figure 2.20a The United States has about 5 percent of the world's population, but it consumes about 25 percent of the world's energy.

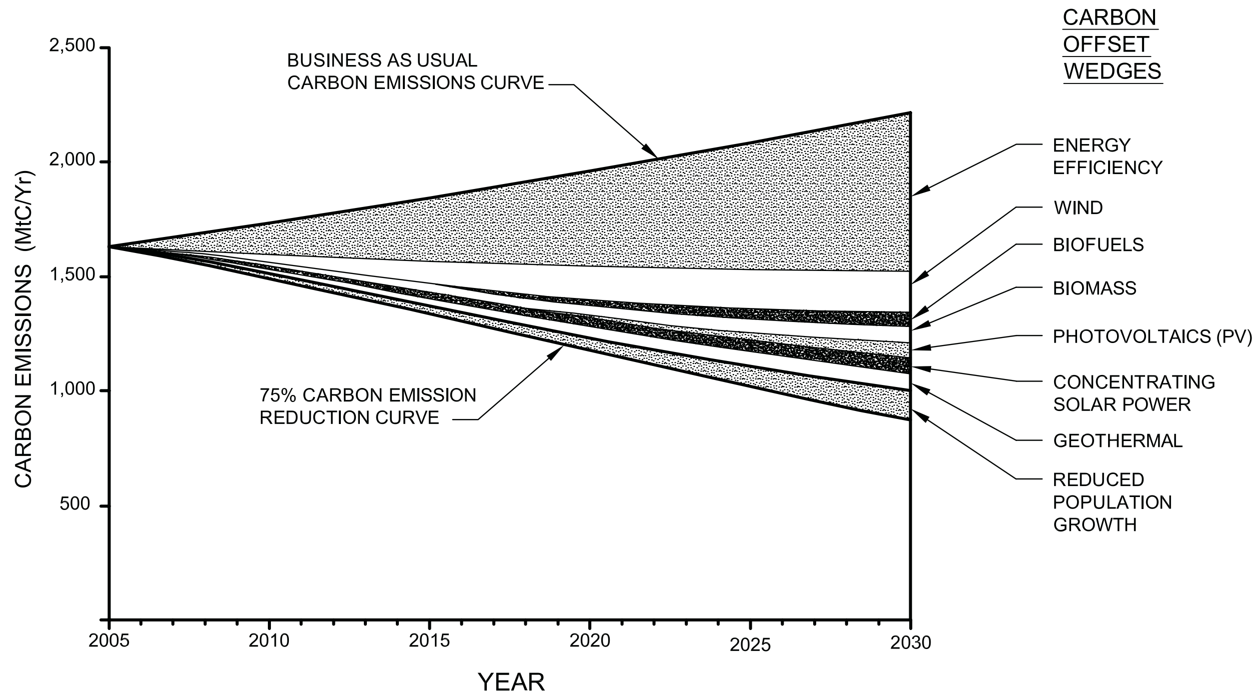


Figure 2.20b To prevent a global warming catastrophe, we must reduce our carbon dioxide emissions from the top curve to the bottom curve by reducing our dependence on fossil energy. By using all of the renewable energy wedges, and especially the efficiency wedge, we can accomplish this most important planetary goal. This graph is based on the work of "stabilization wedges" by Pacala and Socolow (Pacala, 2004).

carbon dioxide than the citizen of any other country (see Table 2.11). The only exceptions are citizens of a few oil-rich countries like Qatar. We also have been producing carbon dioxide for a long time, so as a country we are responsible for just a little less than 30 percent of all the man-made carbon dioxide in the atmosphere (see Table 2.11). We also have the wealth and resources to lead the way. As a leader in research and technology, we can create and share the technical tools needed for creating a sustainable world.

Some people incorrectly assume that nothing can be done about global warming. However, the renewable energies mentioned above, together with efficiency, can radically reduce greenhouse gases and lead us to a sustainable world (Fig. 2.20b).

The following chapters present the information and design tools needed to create aesthetic, energy-conscious buildings. The goal is to reduce the amount of energy that buildings need using the three-tier approach: design of the building itself, use of passive systems, and finally, efficient mechanical systems.

Since heating, cooling, and lighting are consequences of energy manipulation, it is important to understand certain principles of energy. The next chapter reviews some of the basic concepts and introduces other important relationships between energy and objects.

KEY IDEAS OF CHAPTER 2

1. We are squandering the earth's riches, destroying the environment, and changing the climate without regard to the needs of future generations.
2. Sustainability can be achieved by implementing the four Rs: reduce, reuse, recycle, and regenerate.
3. Sustainable design is also known as green, ecological, or environmentally responsible design.
4. The greater the population, the more difficult it is to achieve sustainability.
5. The greater the affluence, the more difficult it is to achieve sustainability.
6. Limitless growth is the enemy of sustainability.
7. Because many important phenomena, such as energy consumption, are exhibiting exponential growth, and because people do not have a good understanding of the implications of exponential growth, improper decisions are being made about the future.
8. Sustainability can be achieved only if we design and build energy-efficient buildings.
9. The massive use of fossil fuels is causing global warming and climate change.

10. At present, most of our energy comes from nonrenewable and polluting energy sources, such as coal, oil, gas, and nuclear energy.
11. Efficiency is the best, quickest, and most cost-effective way to reduce our dependence on fossil and nuclear energy.
12. We must switch to renewable, nonpolluting energy sources such as solar, wind, biomass, hydropower, and geothermal energy.
13. Geo-exchange heat pumps have great potential for energy conservation.
14. Although not a source of energy, hydrogen has the potential to be the clean fuel of the future.
15. As architect Bob Berkabile said, "If a building makes animals or people or the planet sick, it's not beautiful and it's not good design."

References

Bartlett, A. "Forgotten Fundamentals of the Energy Crisis." *American Journal of Physics*, September, 1978, 46–54.

———. "Reflections on Sustainability, Population Growth, and the Environment—Revisited." *Renewable Resources Journal*. Winter 1997, 6–23.

Butti, K., and J. Perdin. *A Golden Thread*. New York: Van Nostrand Reinhold, 1980.

Campbell, C., and J. Laherrère. "The End of Cheap Oil." *Scientific American*, March 1998, 278–281.

FSEC. "Air-Conditioning Use Cut by 80 Percent in Lakeland Research Home, Cocoa, Fl." *Solar Collector*, June–July 1998, 23–28.

Hubbert, K. M. *American Journal of Physics*, vol. 49, no. 11, 1981.

McDonough, W., and M. Braungart. "The Next Industrial Revolution." *Atlantic Monthly*, October 1998, 82–92.

Pacala, S., and Socolow, R. "Stabilization Wedges: Solving the Climate Problem for the Next 50 Years with . . ." *Science* 13, August 2004: 968–972.

Stobaugh, R., and D. Yerkin. *Energy Future—Report of the Energy Project at the Harvard Business School*. New York: Random House, 1979.

World Resource Institute www.wri.org Search: "Searchable Database" for "CO_2 Emissions: Cumulative CO_2 emissions, 1900–2002."

Wylie, A. "Form with a Function." *America West Airlines Magazine*, April 1994, 57–61.

Resources

Further Reading

(See the Bibliography in the back of the book for full citations.)

American Wind Energy Association. *Permitting Small Wind Turbines: A Handbook*.

Bartlett, A. "Reflections on Sustainability, Population Growth, and the Environment—Revisited."

Barnett, D. L., and W. D. Browning. *A Primer on Sustainable Building*.

Campbell, C. J., and J. H. Leherrère. "The End of Cheap Oil."

Commoner, B. *The Politics of Energy*.

Crosbie, M. J. *Green Architecture: A Guide to Sustainable Design*.

Diamond, J. *Colapse: How Societies Choose to Fail or Succeed*.

Crowther, R. Ecologic Architecture. *Environmental Building News*. See Appendix K.

Ehrlich, P. R., and A. H. Ehrlich. *The Population Explosion*.

Gelbspan, R. *The Heat Is On: The High Stakes Battle Over Earth's Threatened Climate*.

Gore, A. *An Inconvenient Truth*.

Hawken, P. *The Ecology of Commerce: A Declaration of Sustainability*.

Hawken, P., A. Lovins, and L. H. Lovins. *Natural Capitalism: Creating the Next Industrial Revolution*.

Lovins, A. B. "More Profit with Less Carbon."

———. *Soft Energy Paths*.

Lovins, A. B., and L. H. Lovins. *Brittle Power: Energy Strategy for National Security*.

Lovins, A. B., et al. *Winning the Oil Endgame*.

Lyle, J. T. *Regenerative Design for Sustainable Development*.

Scheer, H. *A Solar Manifesto: The Need for a Total Solar Energy Supply—And How to Achieve It*.

Singh, M. *The Timeless Energy of the Sun for Life and Peace with Nature*.

Susanka, S., *The Not So Big House*.

Wilson, E. O."Is Humanity Suicidal? We're Flirting with the Extinction of Our Species." *New York Times Magazine*.

Videos

(See Appendix K for full citations and ordering information.)

Affluenza. KCTS Television Arithmetic, Population, and Energy. Dr. Albert A. Bartlett. 65 minutes.

An Inconvenient Truth. Al Gore.

Keeping the Earth: Religious and Scientific Perspectives on the Environment. 27 minutes.

World Population. ZPG.

Organizations

(See Appendix K for full citations and ordering information.)

American Hydrogen Association
(E-mail): aha@getnet.com
www.clean-air.org

American Solar Energy Society
www.ases.org

National Renewable Energy Laboratory
www.nrel.gov
Good source for detailed information on renewables.

Oak Ridge National Laboratory
www.ornl.gov
An excellent source of information on renewable energy and energy efficient building.

Rocky Mountain Institute
www.rmi.org
An excellent source of objective energy information.

Union of Concerned Scientists
www.ucsusa.org

U. S. Department of Energy
www.energy.gov
Portal for all kinds of information from the U. S. government about making buildings energy efficient.

CHAPTER 3

BASIC PRINCIPLES

Solar architecture is not about fashion, it is about survival.
Sir Norman Foster

If we are anything, we must be a democracy of the intellect. We must not perish by the distance between people and government, between people and power. . . . And that distance can only be conflated, can only be closed, if knowledge sits in the homes and heads of people with no ambition to control others, and not up in the isolated seats of power.
J. Bronowski
The Ascent of Man, *1973*

3.1 INTRODUCTION

The heating, cooling, and lighting of buildings are accomplished by adding or removing energy. A good basic understanding of the physics of energy and its related principles is a prerequisite for much of the material in the following chapters. Consequently, this chapter is devoted to both a review of some rather well-known concepts and an introduction to some less familiar ideas such as mean radiant temperature, time lag, the insulating effect of mass, and embodied energy.

3.2 HEAT

Energy comes in many forms, and most of these are used in buildings. Much of this book, however, is concerned with energy in the form of heat, which exists in three different forms:

1. Sensible heat—can be measured with a thermometer
2. Latent heat—the change of state or phase change of a material
3. Radiant heat—a form of electromagnetic radiation

3.3 SENSIBLE HEAT

The random motion of molecules is a form of energy called sensible heat. An object whose molecules have a larger random motion is said to be hotter and to contain more heat (see Fig. 3.3a). Because this type of heat can be measured by a thermometer and felt by our skin, it is called sensible heat. If the two objects in Fig. 3.3a are brought into contact, some of the more intense random motion of the object on the left will be transferred to the object on the right by the heat-flow mechanism called conduction. Since the molecules must be close to each other in order to collide, and since in air the molecules are far apart, air is not a good conductor of heat. A vacuum allows no conduction at all.

Temperature is a measure of the intensity of the random motion of molecules. We cannot determine the heat content of an object just by knowing its temperature. For example, in Figure 3.3b (top), we see two blocks of a certain material that are both at the same temperature. Yet the block on the right will contain twice the heat because it has twice the mass.

The mass alone cannot determine the heat content either. In Figure 3.3b (bottom), we see two blocks of the same size, yet one block has more heat content because it has a higher temperature. Thus, sensible heat content is a function of both mass and temperature. Heat content is also a function of heat capacity, which is discussed in Section 3.15.

In the United States, we still use the Fahrenheit (°F) scale for temperature and the British thermal unit (Btu) as our unit of heat. The rest of the world, including Great Britain, uses the international system of units (SI), where temperature is measured in Celsius (°C) and heat in the joule or calorie. (See Table 3.3.)

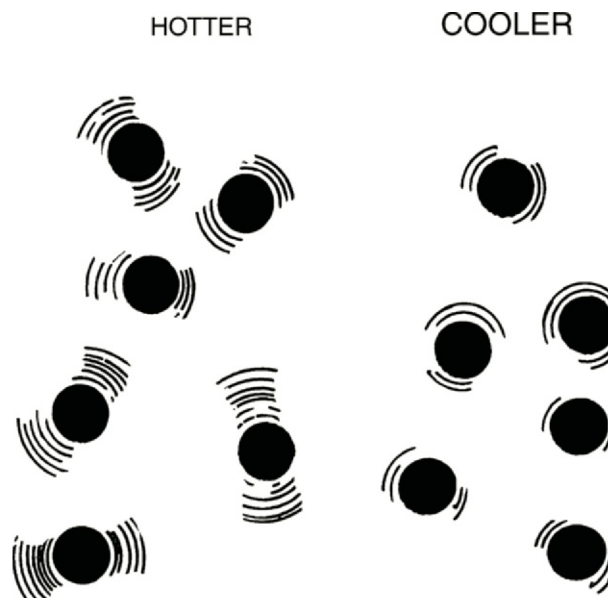


Figure 3.3a Sensible heat is the random motion of molecules, and temperature is a measure of the intensity of that motion.

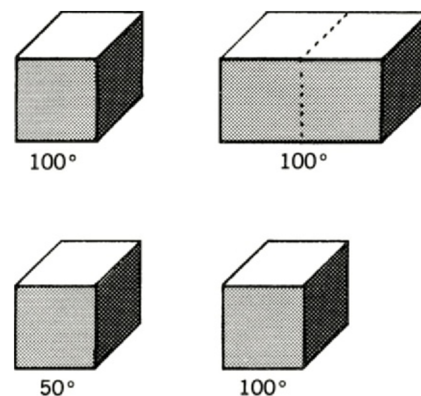


Figure 3.3b The amount of sensible heat is a function of both temperature and mass. In each case, the blocks on the right have twice as much sensible heat content as the blocks on the left.

Table 3.3 Units of Heat and Temperature

	I–P System*	SI System
Heat	British thermal unit (Btu)	joule (J) or calorie (cal)
Heat flow	Btu/hour (Btu/h)	watt (W) or joule/second (J/s)
Temperature	Fahrenheit (°F)	Celsius (°C) or Kelvin (K)**

*I-P = inch-pound.
**A degree Celsius and a degree Kelvin have the same magnitude and are, therefore, interchangeable in many cases. They differ only in what they call zero (i.e., 0 degrees K = −273°C).

3.4 LATENT HEAT

By adding 1 Btu of heat to 1 pound of water, its temperature is raised 1°F (4.2 joules added to a gram of water will raise its temperature 1°C). It takes, however, 144 Btu to change a pound of ice into a pound of water and about 1000 Btu to change a pound of water into a pound of steam (Fig. 3.4). It takes very large amounts of energy to break the bonds between the molecules when a change of state occurs. "Heat of fusion" is required to melt a solid and "heat of vaporization" is required to change a liquid into a gas. Notice also that the water is no hotter than the ice and the steam is no hotter than the water, even though a large amount of heat is added. This heat energy, which is very real but cannot be measured by a thermometer, is called latent heat. In melting ice or boiling water, sensible heat is changed into latent heat, and when steam condenses and water freezes, the latent heat is turned back into sensible heat.

Latent heat is a compact and convenient form for storing and transferring heat. However, since the melting and boiling points of water are not always suitable, other materials called refrigerants are used because they have the melting and boiling temperatures necessary for refrigeration machines.

A change of state is also known as a phase change. Materials that melt at a useful temperature can be used to store heat or be used as a heat sink to cool a building. Such materials are called **phase change materials (PCM)**.

3.5 EVAPORATIVE COOLING

When sweat evaporates from the skin, a large amount of heat is required. This heat of vaporization is drawn from the skin, which is cooled in the process. The sensible heat in the skin is turned into the latent heat of the water vapor.

As water evaporates, the air next to the skin becomes humid and eventually even saturated. The moisture in the air will then inhibit further evaporation. Thus, either air motion to remove this moist air or very dry air is required to make evaporative cooling efficient (Fig. 3.5).

Buildings can also be cooled by evaporation. Water sprayed on the roof can dramatically reduce its temperature. In dry climates, air entering buildings can be cooled with

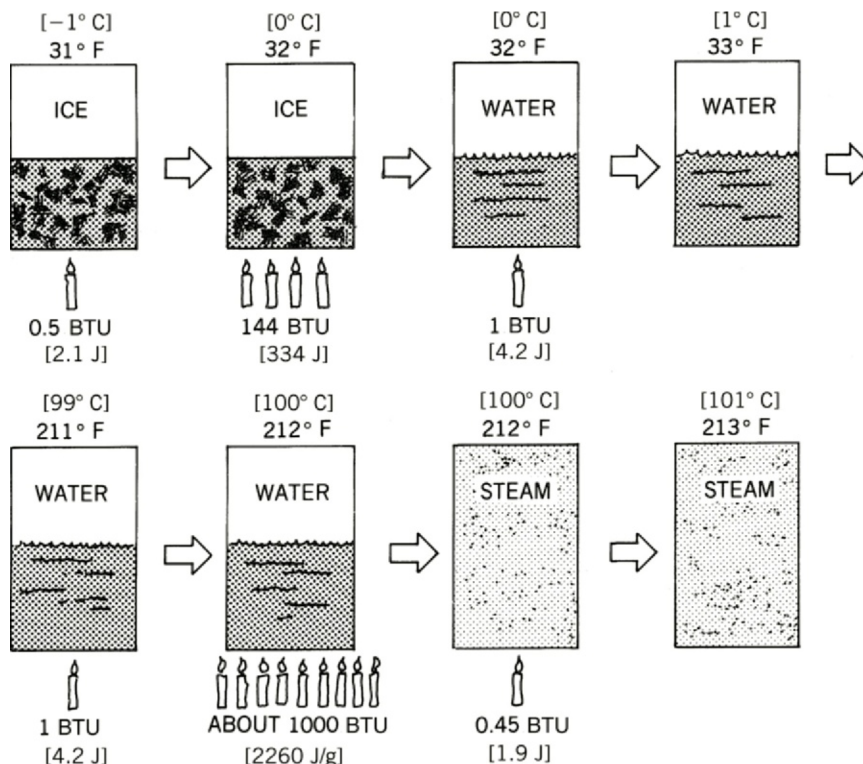


Figure 3.4 Latent heat is the large amount of energy required to change the state of a material (phase change), and it cannot be measured by a thermometer. The values given here are for 1 lb or 1 g of water, ice, or steam.

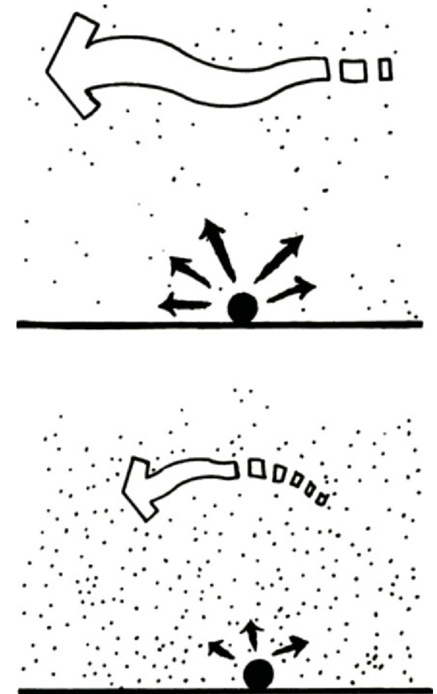


Figure 3.5 The rate of evaporative cooling is a function of both humidity and air movement. Evaporation is rapid when the humidity is low and air movement is high. Evaporation is slow when the humidity is high and air movement is low.

water sprays. Such techniques will be described in Chapter 10.

3.6 CONVECTION

As a gas or liquid acquires heat by conduction, the fluid expands and becomes less dense. It will then rise by floating on top of denser and cooler fluid, as seen in Figure 3.6a. The resulting currents transfer heat by the mechanism called natural convection. This heat-transfer mechanism is very much dependent on gravity and, therefore, heat never convects down. Since we are surrounded by air, natural convection in air is a very important heat-transfer mechanism in our goal of being comfortable.

When there is no air motion due to the wind or a fan, natural convection currents tend to create layers that are at different temperatures. In rooms, hot air collects near the ceiling and cold air near the floor (Fig. 3.6b). This **stratification** can be an asset in the summer and a liability in the winter. Strategies to deal with this phenomenon will be discussed throughout this book. A similar situation occurs in still lakes where surface water is much warmer than deep water (Fig. 3.6b).

A different type of convection occurs when the air is moved by a fan or by the wind, or when water is moved by a pump (Fig. 3.6c). When a fluid (gas or liquid) is circulated between hotter and cooler areas, heat will be transferred by the mechanism known as forced convection.

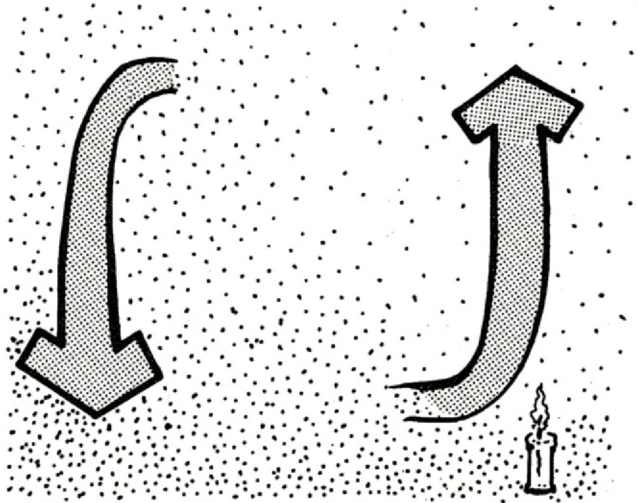


Figure 3.6a Natural convection currents result from differences in temperature.

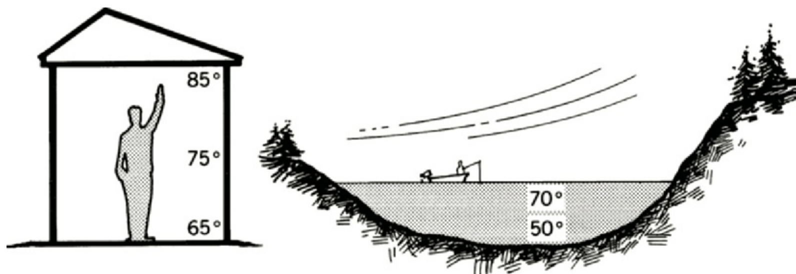


Figure 3.6b Stratification results from natural convection unless other forces are present to mix the air or water. (See also Colorplates 3 and 4.)

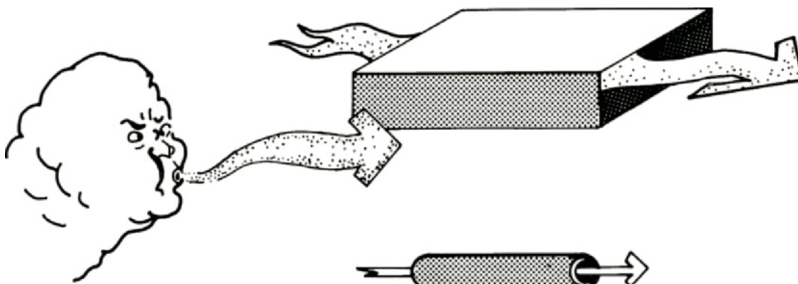


Figure 3.6c Forced convection is caused by wind, fans, or pumps.

3.7 TRANSPORT

In the eighteenth and nineteenth centuries, it was common to use warming pans to preheat beds. The typical warming pan, as shown in Figure 3.7, was about 12 in. (30 cm) in diameter and about 4 in. (10 cm) deep, and it had a long wooden handle. It was filled with hot embers from the fireplace, carried to the bedrooms, and passed between the sheets to remove the chill. In the early twentieth century,



Figure 3.7 Warming pans and hot-water bottles were popular in the past to transport heat from the fireplace or stove to cold beds.

it was common to use hot-water bottles for the same purpose. This transfer of heat by moving material is called transport. Because of its convenience, forced convection is much more popular today for moving heat around a building than is transport.

3.8 ENERGY-TRANSFER MEDIUMS

In both the heating and cooling of buildings, a major design decision is the choice of the energy-transfer medium. The most common alternatives are air and water. It is, therefore, very valuable to understand the relative heat-transfer capacity of these two materials. Because air has both much lower density and much less specific heat than water, much more of it is required to store or transfer heat. To store or transfer equal amounts of heat, a volume of air about 3000 times greater than that of water is needed (Fig. 3.8).

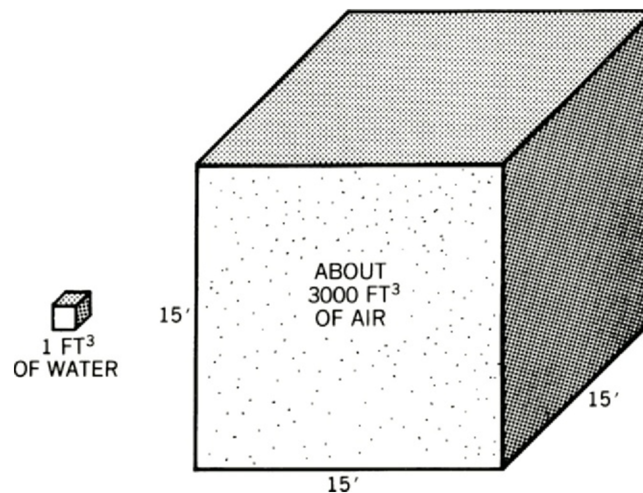


Figure 3.8 One cubic foot or 1 liter of water can store or transfer the same amount of heat as over 3000 ft^3 or 3000 liters of air.

3.9 RADIATION

The third form of heat is radiant heat. All parts of the electromagnetic spectrum transfer radiant energy. All bodies facing an air space or a vacuum emit and absorb radiant energy continuously. Hot bodies lose heat by radiation because they emit more energy than they absorb (Fig. 3.9a). Objects at room temperature radiate in the long-wave infrared region of the electromagnetic spectrum, while objects hot enough to glow radiate in the visible part of the spectrum. Thus, the wavelength or frequency of the radiation emitted is a function of the temperature of the object.

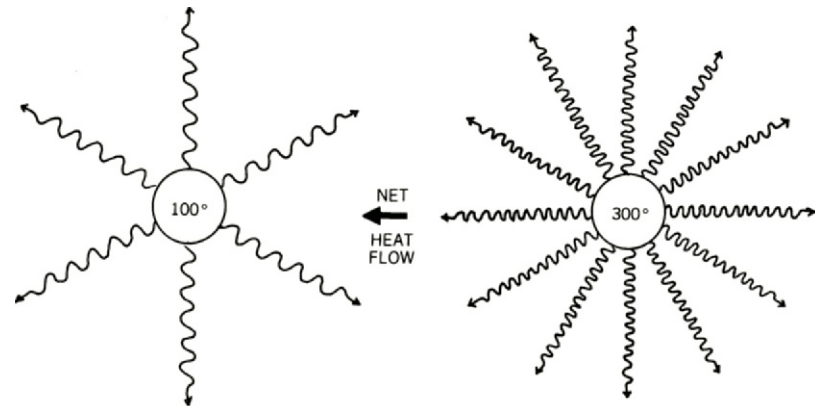


Figure 3.9a Although all objects absorb and emit radiant energy, there will be a net radiant flow from warmer to cooler objects.

Since radiation is not affected by gravity, a body will radiate down as much as up. Radiation is, however, affected by the nature of the material with which it interacts and especially the surface of the material. The four possible interactions, as illustrated in Figure 3.9b, are as follows:

1. Transmittance—the situation in which radiation passes through the material.
2. Absorptance—the situation in which radiation is converted into sensible heat within the material.
3. Reflectance—the situation in which radiation is reflected off the surface.
4. Emittance—the situation in which radiation is given off by the surface, thereby reducing the sensible heat content of the object. Polished metal surfaces have low emittance, while most other materials have high emittance.

For opaque materials the absorptance and reflectance both tell the same story. A high reflectance surface will be a low absorptance surface and vice versa (Fig. 3.9c).

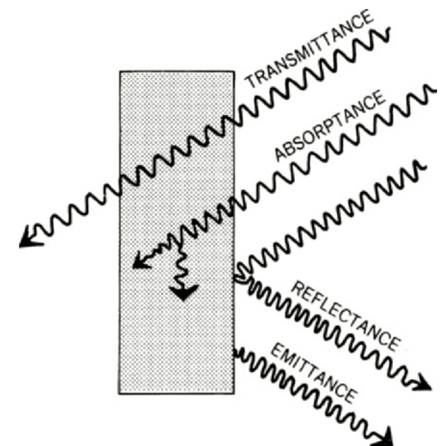


Figure 3.9b Four different types of interaction are possible between radiant energy and matter.

The type of interaction that will occur is a function not only of the material but also of the wavelength of the radiation. For example, glass interacts very differently with solar radiation (short-wave) than with thermal radiation (long-wave infrared), as shown in Figure 3.9d. Glass is mostly transparent to short-wave radiation and opaque to long-wave radiation. The long-wave radiation is mostly absorbed, thereby heating up the glass. Much of the absorbed radiation is then reradiated from the glass inward and outward. The net effect is that some of the long-wave radiation is blocked by the glass. The greenhouse effect, explained below, is partly due to this property of glass and most plastics used for glazing. Polyethelene is the major exception, since it is transparent to infrared radiation.

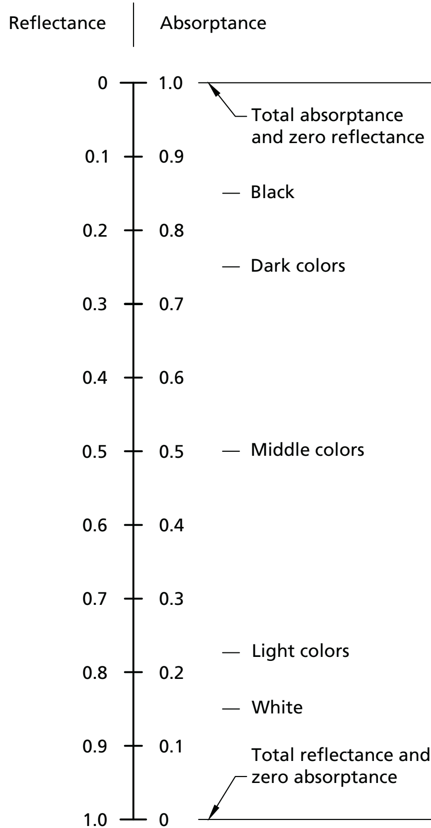


Figure 3.9c The type of interaction depends not only on the nature of the material but also on the wavelength of the radiation.

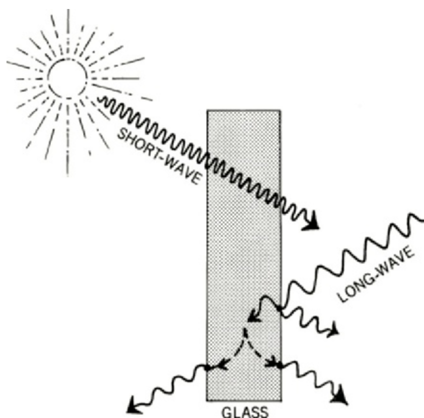


Figure 3.9d Glass has high transmittance to short-wave radiation (e.g., solar radiation), but it absorbs and reflects long-wave infrared radiation (ie.g., heat radiation). The interaction depends on the wavelength, or frequency, of the radiation.

3.10 GREENHOUSE EFFECT

The concept of the greenhouse effect is vital for understanding both solar energy and climate change. The greenhouse effect is due to the fact that the type of interaction that occurs between a material and radiant energy depends on the wavelength of that radiation.

Figure 3.10a illustrates the basic concept of the greenhouse effect. The short-wave solar radiation is able to pass easily through the glass, whereupon it is absorbed by indoor objects. As these objects warm up, they increase their emission of radiation in the long-wave portion of the electromagnetic spectrum. Since glass is opaque to this radiation, much of the energy is trapped. The glass has created, in effect, a heat trap, and the indoor temperature begins to rise.

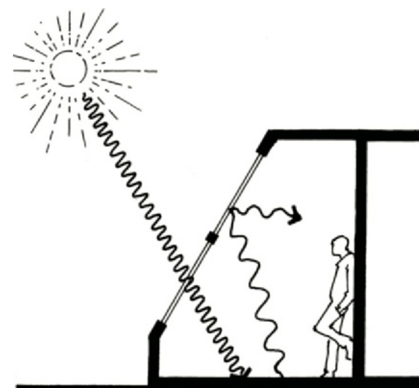


Figure 3.10a The greenhouse effect is a consequence of the fact that glazing transmits short-wave but blocks long-wave radiation.

To better understand this very important concept, let us look at the vertically aligned graphs in Figure 3.10b. First, look at the top graph, which describes the behavior of glass with respect to radiation. The percentage transmission is given as a function of the wavelength of the radiation. Notice that glass has a very high transmission for radiation between 0.3 and 3 μm (millionth of a meter) and zero transmission for radiation above and below that "window."

The bottom graph of Figure 3.10b shows the wavelengths of the solar radiation reaching the earth. It consists of about 5 percent ultraviolet (UV), about 45 percent visible light, and about 50 percent solar infrared (IR). The bottom graph also shows the wavelengths of radiation emitted by objects at room temperature, which are also part of the infrared spectrum. To distinguish these from the solar infrared, they are called long-wave infrared and, consequently, the solar infrared is also called short-wave infrared.

The graphs together show that the part of the electromagnetic spectrum for which glass is transparent corresponds to solar radiation, and the part for which glass is opaque corresponds to the long-wave infrared heat radiation given off by objects at room temperature. The solar radiation enters through the glass and is absorbed by objects in the room. These objects heat up and then increase their reradiation in the long-wave infrared part of the spectrum. Since glass is opaque to this radiation, much of the energy is trapped and the room heats up. This is one of the mechanisms that causes a greenhouse to warm up. The other mechanism of the greenhouse effect is the obvious fact that the glazing stops the convective loss of hot air. These mechanisms together form a very effective heat trap.

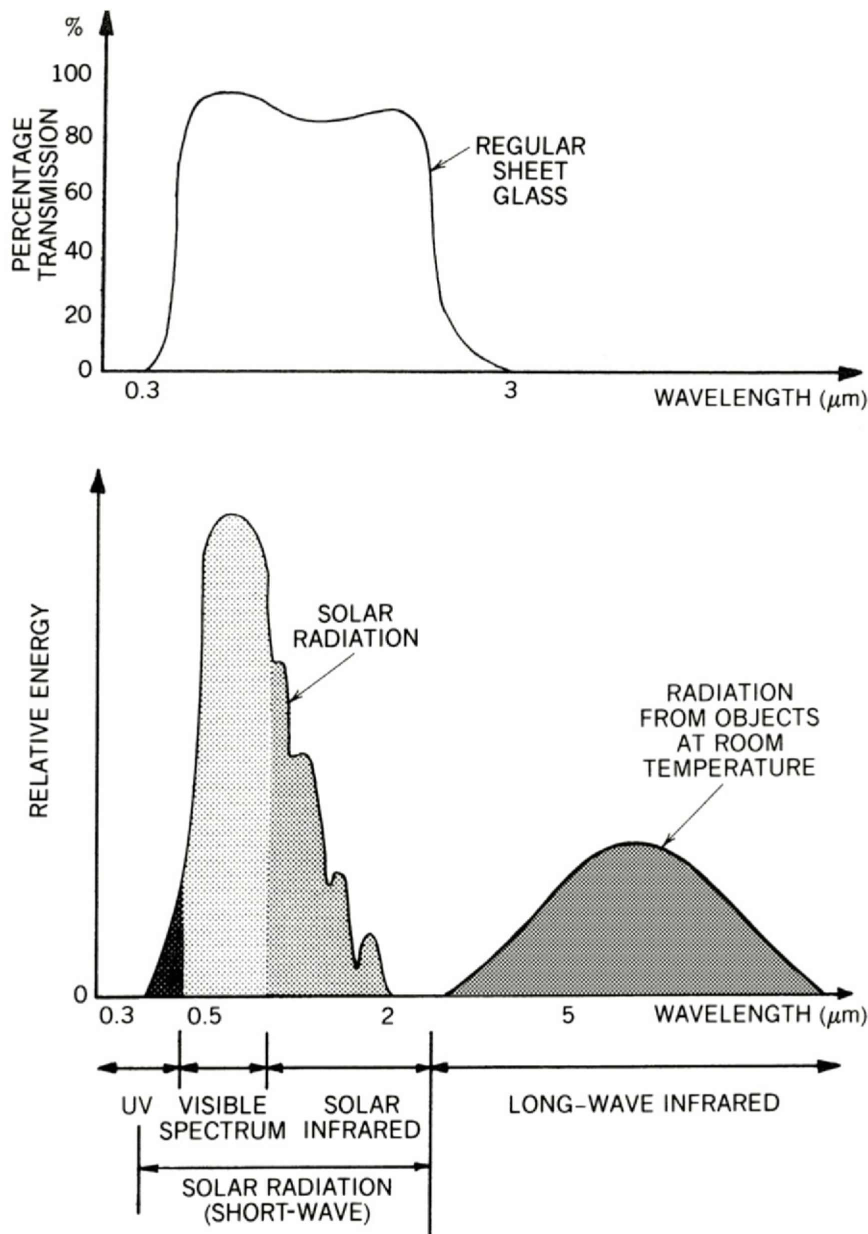


Figure 3.10b Note that these two graphs are aligned vertically. Thus, the top graph shows that glass transmits about 90 percent of both the visible and short-wave infrared portions of sunlight. It also shows that glass does not transmit any of the long-wave infrared radiation emitted by objects at room temperature.

Note that glass changes from 0 to about 80 percent transmission in the ultraviolet part of the spectrum. Thus, the longer wavelengths of UV pass through the glass, while the shorter UV, which cause sunburn, do not. The longer UV radiation contributes to both solar heating and the fading of colors.

3.11 EQUILIBRIUM TEMPERATURE OF A SURFACE

Understanding the heating, cooling, and lighting of buildings requires a fair amount of knowledge of the behavior of radiant energy. For example, what is the best color for a solar collector, and what is the best color for a roof to reject solar heat in the summer? Figure 3.11 illustrates how surfaces of different colors and finishes interact with radiant energy. To understand why a black metal plate will get much warmer in the sun than a white metal plate, we must remember that materials vary in the way they emit and absorb radiant energy. The balance between absorptance and emittance determines how hot the plate will get, the **equilibrium temperature**. Black has a much higher equilibrium temperature than white because it has a much higher absorptance factor. However, black is not the ideal collector of radiant energy because of its high emissivity. Its equilibrium temperature is suppressed because it reradiates much of the energy it has absorbed.

To increase efficiency in solar collectors, a type of **selective surface** was developed. These finishes have the same high absorptance as black but are stingier in emitting radiation. Thus, their equilibrium temperature is very high.

White is the best color to minimize heat gain in the summer because it is not only a poor absorber but also a good emitter of any energy that is absorbed. Thus, white neither likes to collect nor keep heat, and a very low equilibrium temperature results. This low surface temperature minimizes the heat gain to the material below the surface.

Polished-metal surfaces, such as shiny aluminum, can be used as radiant barriers because they neither absorb nor emit radiation readily. For this reason, aluminum foil is sometimes used in buildings as a radiant barrier. However, the equilibrium temperature of a polished-metal surface is higher than that of a white surface because the metal does not emit whatever it has absorbed. Although both white and polished metals absorb about the same small percentage of sunlight, white is a much better emitter of heat radiation and so will be cooler in the sun than a polished-metal surface.

SURFACE COLOR	WHITE	SHINY METAL	BLACK	SELECTIVE COATING
SHORT-WAVE (SOLAR ABSORBTANCE)	LOW	LOW	HIGH	HIGH
LONG-WAVE EMITTANCE	HIGH	LOW	HIGH	LOW
EQUILIBRIUM TEMPERATURE	COOL	WARM	HOT	VERY HOT

SURFACE COLOR → BASE MATERIAL →

Figure 3.11 The equilibrium temperature is a consequence of both the absorptance and the emittance characteristics of a material. If these colors were the finishes of automobiles, it would be easy to predict which would be hotter and which cooler.

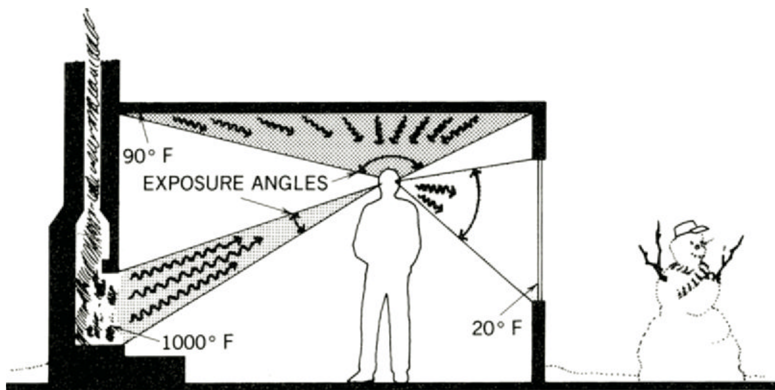


Figure 3.12 The mean radiant temperature (MRT) at any point is the combined effect of the temperature and angle of exposure of all surfaces in view.

SIDEBOX 3.12

Mean Radiant Temperature

MRT is the weighted average radiant temperature of a point in space, and it varies from point to point. The most precise calculation would use solid angles, but for simplicity, the following two-dimensional version in plan or section is often used:

$$\mathrm{MRT}_A = \frac{\sum T \cdot \Theta}{360} = \frac{T_1 \cdot \Theta_1 + T_2 \cdot \Theta_2 + T_3 \cdot \Theta_3 + \cdots}{360^\circ}$$

where

MRT_A = mean radiant temperature for point A
T = temperature of a surface
Θ = exposure angle of a surface from the point being considered

3.12 MEAN RADIANT TEMPERATURE

To determine if a certain body will be a net gainer or loser of radiant energy, we must consider both the temperature and the exposure angle of all objects that are in view of the body in question. The mean radiant temperature (MRT) describes the radiant environment for a point in space (see Sidebox 3.12). For example, the radiant effect on one's face by a fireplace (Fig. 3.12) is quite high because the fire's temperature at about 1000°F (540°C) more than compensates for the small angle of its exposure. A radiant ceiling can have just as much of a warming effect but with a much lower temperature (90°F) (32°C) because its large area creates a large exposure angle. The radiant effect can also be negative, as in the case of a person standing in front of a cold window.

Walking toward the fire (Fig. 3.12) would increase the MRT, while walking toward the cold window would reduce it because the relative size of the exposure angles would change. Many a "cold draft" near large windows in winter is actually a misinterpretation of a low MRT. The significant effect MRT has on thermal comfort is further explained in the next chapter.

3.13 HEAT FLOW

Heat flows naturally from a higher temperature to a lower temperature but not necessarily from more heat to less heat. To better understand this, we can consider a water analogy. In this analogy, the height between different levels of water represents the temperature difference between two heat sources and the volume of water represents the amount of heat.

When both reservoirs are at the same level, as shown in Figure 3.13 (top), there is no flow. The fact that there is more water (heat) on one side than the other is of no consequence.

If, however, the levels of the reservoirs are not the same, then flow

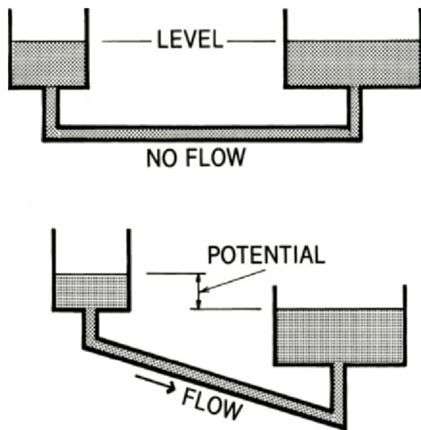


Figure 3.13 A water analogy shows how temperature, not heat content, determines heat flow.

occurs, as indicated in Figure 3.13 (bottom). Notice that this occurs even when the amount of water (heat) is less on the higher side. Just as water will flow only down, so heat will flow only from a higher temperature to a lower temperature.

To get the water to a higher level, some kind of pump is required. Heat, likewise, can be raised to a higher temperature only by some kind of "heat pump," which works against the natural flow. Refrigeration machines, the essential devices in air conditioners and refrigerators, pump heat from a lower to a higher temperature. They will be explained in some detail in Chapter 16.

In the I–P system, heat flow is measured in Btu per hour (Btu/h). For example, the heat loss from a building is measured in Btu/h, and the rating of a furnace, which describes the rate at which heat is delivered, is also given in Btu/h. In the SI system, heat flow is described by watts (W), which are equal to joules per second (J/s) (see again Table 3.3).

3.14 HEAT SINK

It is easy to see how transporting hot water to a room also supplies heat to the room. It is not so obvious, however, to see how supplying chilled water cools the room. Are we supplying "coolth"? This imaginary concept only confuses and should not be used. The correct and very useful concept is that of a heat sink. In Figure 3.14 (top) the room is cooled by the chilled water that is acting as a heat sink. The chilled water soaks up heat and gets warmer while the room gets cooler.

Often the massive structure of a building acts as a heat sink. Many massive buildings feel comfortably cool on hot summer days, as in Figure 3.14 (bottom). During the night, these buildings give up their heat by convection to the cool night air and by radiation to the cold sky—thus recharging their heat-sink capability for the next day. However, in very humid regions the high nighttime temperatures prevent effective recharging of the heat sink; consequently, massive buildings are not helpful as heat sinks in very humid climates.

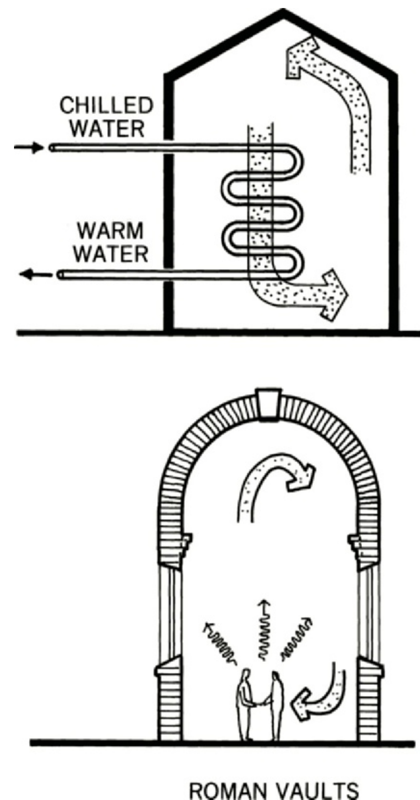


Figure 3.14 The cooling effect of a heat sink can result from a cold fluid or from the mass of the building itself.

3.15 HEAT CAPACITY

The amount of heat required to raise the temperature of a material 1°F (1°C) is called the heat capacity of that material. The heat capacity of different materials varies widely, but in general, heavier materials have a higher heat capacity. Water is an exception in that it has the highest heat capacity even though it is a middleweight material (Fig. 3.15). In architecture we are usually more interested in the heat capacity per volume than in the heat capacity per weight, which is more commonly known as specific heat.

Also note again the dramatic difference in heat capacity between air and water, as shown in Figure 3.8. This clearly indicates the reason water is so often used to store or move heat. See Figure 7.17a for the heat capacity of various common materials.

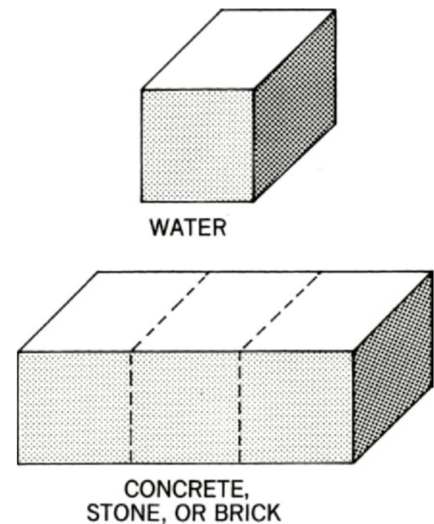


Figure 3.15 If the container of water and the concrete block are at the same temperature, they will contain the same amount of sensible heat. Because it takes only one-third as much water to hold the same amount of heat as concrete, water has three times the volumetric heat capacity of concrete.

3.16 THERMAL RESISTANCE

The opposition of materials and air spaces to the flow of heat by conduction, convection, and radiation is called thermal resistance. By knowing the resistance of a material, we can predict how much heat will flow through it and can compare materials with each other. The thermal resistance of building materials is largely a function of the number and size of air spaces that they contain. For example, 1 in. or 1 cm of wood has the same thermal resistance as 12 in. or 12 cm of concrete mainly because of the air spaces created by the cells in the wood (Fig. 3.16). However, this is true only under steady-state conditions, where the temperatures across a material remains constant for a long period of time. Under certain dynamic temperature conditions, 12 in. or 12 cm of concrete can appear to have more resistance to heat flow than 1 in. or 1 cm of wood. To understand this, we must consider the concept of time lag, explained in Section 3.18. Because the units of thermal resistance are complex and hard to remember, technical literature frequently gives the thermal resistance in terms of R-value (see Sidebox 3.16).

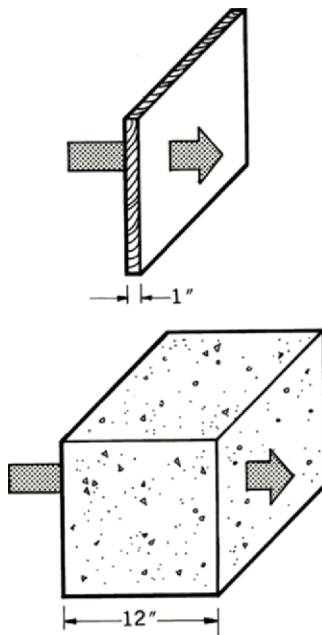


Figure 3.16 The heat flow is equal through the two materials because the thermal resistance of wood is twelve times as great as that of concrete.

SIDEBOX 3.16

In I-P units, thermal resistance in R-value $= \dfrac{ft^2 \times °F}{Btu/h}$

where Btu/h = heat flow per hour
or in SI

$$\text{RSI-value} = \frac{m^2 \times °C}{W}$$

where
m = meter
°C = degrees Celsius
W = watts

Ordinary building materials and their air spaces resist heat that is flowing by the mechanisms of conductance and convection, while **radiant barriers** resist the heat flowing by radiation through air or a vacuum. The most common radiant barriers are made of aluminum foil because of its relatively low cost and because it has both a high reflectance and low emittance (see Figure 15.6c).

3.17 HEAT-FLOW COEFFICIENT

Much of the technical literature describes the thermal characteristics of wall or roof systems in terms of the heat-flow coefficient *U* rather than the total thermal resistance *R*. Because the heat-flow coefficient is a measure of heat flow, it is the reciprocal of thermal resistance (see Sidebox 3.17).

SIDEBOX 3.17

$$U = \frac{1}{R_T}$$

where
U = U-coefficient
R_T = total resistance = $\sum R = R_1 + R_2 + R_3 + \cdots$

3.18 TIME LAG

Consider what happens when two walls with equal thermal resistance but with a different mass are first exposed to a temperature difference. Although 12 in. or 12 cm of concrete and 1 in. or 1 cm of wood have the same thermal resistance, they do not have the same heat capacity. The 12 in. or 12 cm concrete wall will have twenty-four times the heat capacity of the 1 in. or 1 cm wood wall.

If the temperature difference across both walls is the same, equal amounts of heat will start flowing through both walls. However, the initial heat to enter will be used to raise the temperature of each material. Only after the walls have substantially warmed up can heat reach the indoors. This delay in heat transfer is very short for the 1 in. or 1 cm wooden wall because of its low heat capacity, while it is much longer for the concrete wall with its high heat capacity. This delay of heat-flow is a phenomenon known as **time lag**.

The concept of time lag can be understood more easily by means of a water analogy in which pipe friction represents thermal resistance and an in-line storage tank represents the thermal capacity of a material (Fig. 3.18). The small tank represents 1 in. (1 cm) of wood (small heat capacity) and the large tank represents 12 in. (12 cm) of concrete (large heat capacity). After four hours, water (heat) is

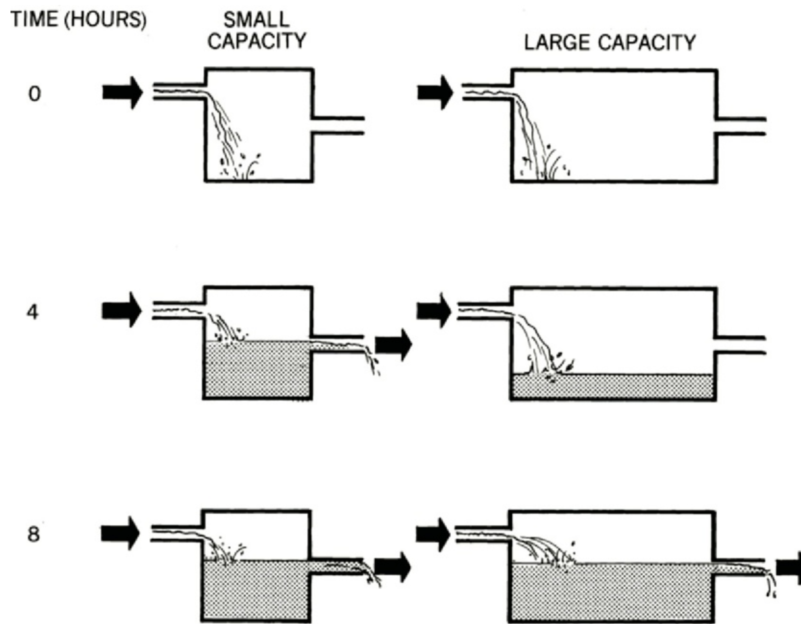


Figure 3.18 This water analogy of time lag illustrates how high storage capacity delays the passage of water under dynamic conditions. Similarly, high heat capacity delays the transmission of heat under dynamic conditions. This example is analogous to heat flowing through either 1 in. or 1 cm of wood (small capacity) and 12 in. or 12 cm of concrete (high capacity).

flowing through the pipe with the low capacity but not through the system with the high capacity. Thus, high-capacity materials have a greater time lag than low-capacity materials. Also note that the time lag ends when the storage tanks are full. Under steady-state conditions there is no time lag.

3.19 INSULATING EFFECT OF MASS

If the temperature difference across a massive material fluctuates in certain specific ways, then the massive material will act as if it had high thermal resistance. Consider a massive concrete house in the desert on a hot summer day. A wall of this building is shown at three different times of day (Fig. 3.19). At 11 A.M. the indoor temperature is lower than the outdoor temperature and heat will flow inward. However, most of this heat is diverted to raising the temperature of the wall.

At 4 P.M. the outdoor temperature is very high. Although some heat is now reaching the indoors, much of the heat is still being used to further raise the temperature of the wall.

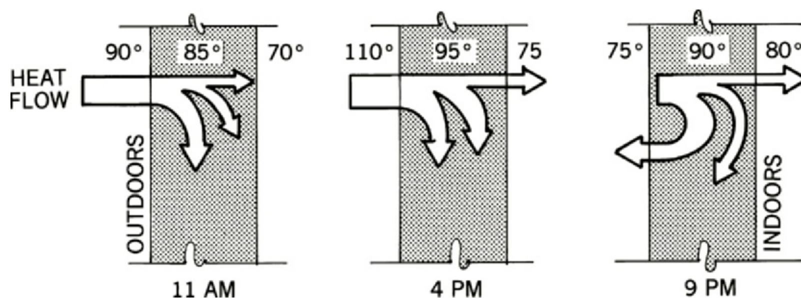


Figure 3.19 The insulating effect of mass is most pronounced in hot and dry climates in the summer. The same wall is shown at three different times of the day. Note that much of the heat entering the wall never makes it to the indoors.

However, at 9 P.M. the outside temperature has declined enough to be below the wall temperature. Now most of the heat that was stored in the wall is flowing outward without ever reaching the interior of the house. In this situation, the time lag of the massive material "insulated" the building from the high outdoor temperatures. It is important to note that the benefits of time lag occur only if the outdoor temperature fluctuates. Also, the larger the daily temperature swing, the greater the insulating effect of the mass. Thus, this insulating effect of mass is most beneficial in hot and dry climates during the summer. This effect is not very helpful in cold climates where the temperature remains consistently below the indoor temperature, and it is only slightly helpful in humid climates, where the daily temperature range is small. In very humid climates, the thermal mass can be a liability and should be avoided if the building is naturally ventilated.

3.20 ENERGY CONVERSION

The first law of thermodynamics states that energy can be neither created nor destroyed, only changed in form. But while energy is never lost, the second law of thermodynamics states that its ability to do work can decline. For example, high-temperature steam can generate electricity with a steam turbine, while the same amount of heat in the form of warm water cannot perform this task. Electricity is a very high-grade, valuable energy form, and to use it to purposely generate low-grade heat is a terrible waste. Sunlight is another high-grade energy source. It should be used to daylight a building before it turns into heat.

Whenever energy is converted into a different form, there will be a loss. Figure 3.20 shows the conversion of a fossil fuel into electricity. The low efficiency (approximately 30 percent) is a consequence of the large number of conversions required. Thus, electrical

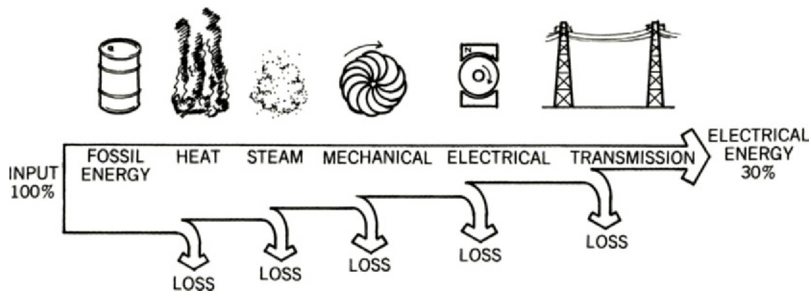


Figure 3.20 In the conversion of fossil fuel into electricity, about 70 percent of the original source energy is lost.

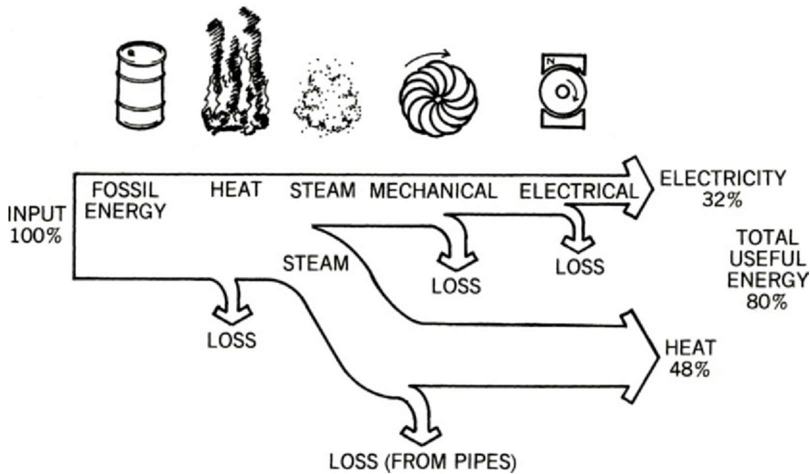


Figure 3.21a Because combined-heat-and-power (CHP) systems generate electricity at the building site, they are able to utilize much of the heat normally wasted at the power plant, and they eliminate the transmission losses.

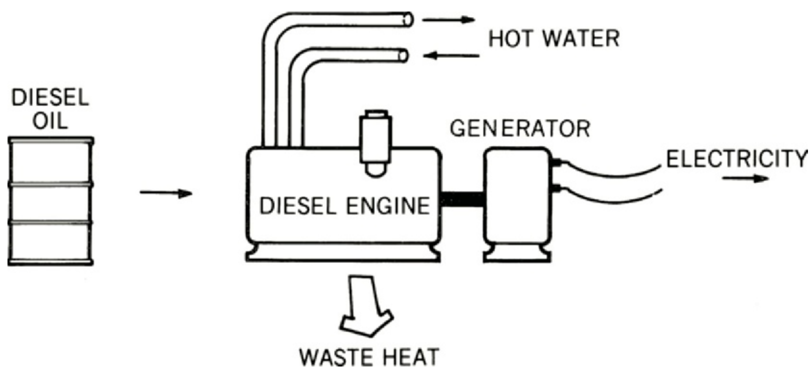


Figure 3.21b Packaged CHP units are self-contained and easily integrated into a building. The fuel could be natural gas, gasoline, diesel oil, or biodiesel oil.

energy should not be used when a better alternative is available. For example, heating directly with natural gas can be more than 90 percent efficient. It is important, however, to note that this example does not argue for the use of fossil fuels, either at the power plant or in the home. As the rest of the book explains, there are better ways to heat, cool, and light our buildings.

3.21 COMBINED HEAT AND POWER

Combined heat and power (CHP), also known as cogeneration, can greatly reduce the energy losses in producing electricity. Through the generation of electricity at the building site, efficiencies of up to 80 percent are possible. Heat, normally wasted at the central power plant, can be used for domestic hot-water or space heating (Fig. 3.21a). Also, overland electrical-transmission losses are almost completely eliminated. Compact and fairly maintenance-free packaged CHP units are commercially available for all sizes of buildings (Fig. 3.21b).

Even more efficient is **trigeneration**, where the waste heat is used not only for heating and hot water but also for cooling in the summer. An absorption refrigeration unit (see Section 16.9) can be powered by the waste heat given off by an engine/generator producing electricity.

3.22 FUEL CELLS

Combined Heat and Power (CHP) can be even more efficient if a fuel cell is used to generate the electricity. Because fuel cells are safe, clean, noiseless, low-maintenance, and compact, they can be placed in any building. Thus, as in CHP, there are no transmission losses, and the waste heat can be used (Fig. 3.22).

Fuel cells are powered with hydrogen that combines with oxygen in the air to form water, electricity, and heat. No emissions pollute the air or cause global warming. No flue is needed. A green high-rise building, 4 Times Square in New York City, uses two fuel cells, located on the fourth floor, to generate a significant portion of the electrical load. Because the building does not have access to a supply of hydrogen, natural gas is used and reformed into hydrogen and carbon dioxide. However, much less carbon dioxide is produced than in conventional natural gas systems because of the high efficiency of the fuel cells.

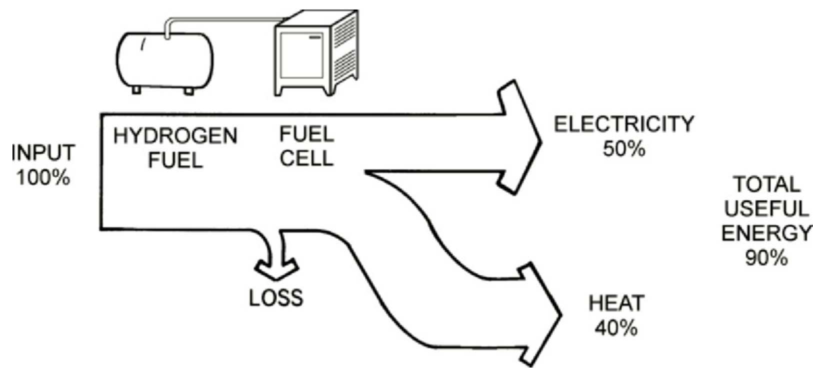


Figure 3.22 Because fuel cells use hydrogen to directly generate electricity and useful heat right inside buildings, about 90 percent of the original energy can be utilized. Fuel cells run off of nonpolluting hydrogen.

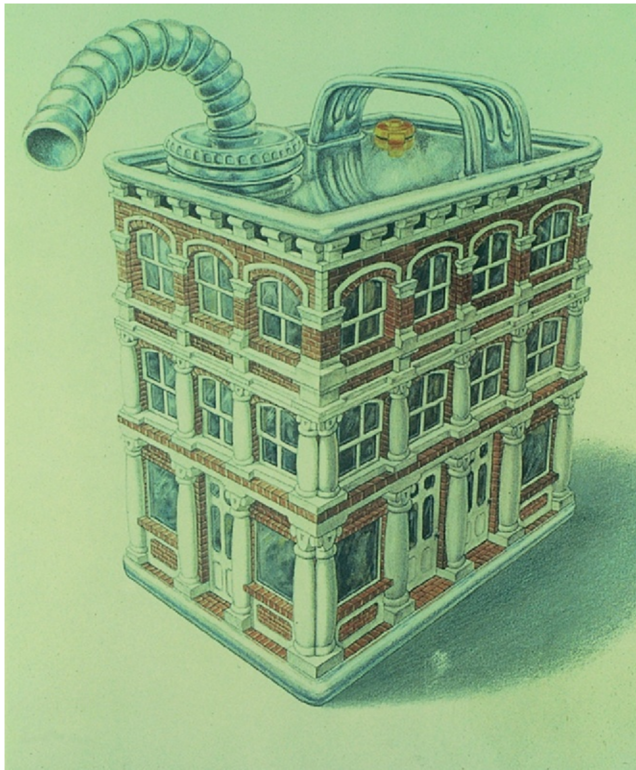


Figure 3.23 A large amount of embodied energy can be saved when existing buildings are reused. (From a poster, copyright 1980, by the National Trust for Historic Preservation.)

It is very important to again note that hydrogen is not a source of energy but rather a way to store energy. Hydrogen has to be made by means of energy-intensive processes such as electrolysis, in which electricity splits the water molecule into hydrogen and oxygen. Fuel cells have their greatest potential to create sustainable buildings when fueled with hydrogen made from renewable sources of energy, such as wind or photovaetics.

3.23 EMBODIED ENERGY

Most discussions of energy and buildings are concerned with the use and operation of a building. It is now recognized that it can take large quantities of energy to construct a building. This embodied energy is a result of both the construction machinery and the energy required to make and transport the materials. For example, aluminum embodies four times as much energy as steel and about twelve times as much as wood. The embodied energy in a modern office building is about the same as the amount of energy the building will consume in twenty years. However, if the new building is very energy efficient, the embodied energy might equal sixty years of operational energy.

Much of the embodied energy can be saved when we recycle old buildings. Thus, conservation of energy is a strong argument for adaptive reuse and historic preservation (Fig. 3.23).

The greenest building is the one that has already been built!
—Carl Elefante, architect

3.24 CONCLUSION

The basic principles described in this chapter will be applied throughout this book. Many of these ideas will make more sense when their applications are mentioned in later chapters. It will often prove useful to refer back to these explanations, although more detailed explanations will be given when appropriate. Special concepts, such as those related to lighting, will be explained when needed.

KEY IDEAS OF CHAPTER 3

1. Sensible heat is the type of heat that can be measured with a thermometer. Dry air has only sensible heat.
2. Heat energy absorbed or given off as a material changes phase is called latent heat. It is also called heat of vaporization and heat of fusion, and it cannot be measured with a thermometer. Air has latent heat when it has water vapor.
3. Heat is transferred by conduction, convection, radiation, and transport.
4. Stratification of temperatures results from natural convection.
5. Water can hold about 3000 times as much heat as an equal volume of air. Therefore, we say that water has a much greater heat capacity than air.
6. Matter and energy interact in four ways:
   a. Transmittance
   b. Absorptance
   c. Reflectance
   d. Emittance
7. The greenhouse effect traps heat by allowing most short-wave radiation to be admitted while blocking most long-wave radiation from leaving.
8. The equilibrium temperature of an object sitting in the sun is a result of the relative absorptance and emittance characteristics of the exposed surface.
9. The mean radiant temperature (MRT) describes the radiant environment. An object will simultaneously gain radiation from hotter objects and lose radiation to cooler objects.
10. A cooler object is a potential heat sink. Chilled water or a massive building cooled overnight can act as a heat sink to cool the interior of a building.
11. Thermal resistance is a measure of a material's resistance to heat flow by the mechanisms of conduction, convection, and radiation.
12. Time lag is the phenomenon describing the delay of heat flow through a material. Massive materials have more time lag than light materials.
13. A radiant barrier (usually made of aluminum foil) can significantly reduce heat flow by radiation.
14. Under certain dynamic temperature conditions, the time lag of massive materials can resist heat flow.
15. The second law of thermodynamics tells us that usable energy is lost every time energy is converted from one form to another. As a consequence, heating a home directly with gas can be 90 percent efficient, while heating with resistance electricity, which was generated by gas, is only 30 percent efficient.
16. Combined heat and power (CHP), also called cogeneration systems, produce electricity where it is needed thereby eliminating transmission losses. Also, the waste heat can be used to heat the building and hot water.
17. Fuel cells have the potential to efficiently generate electricity and supply useful heat as a by-product inside buildings with little or no pollution. But hydrogen must be made, and, therefore, is not a source of energy. Hydrogen made from renewable sources of energy will be sustainable.
18. The energy needed to construct a building is the embodied energy of that building. When buildings are demolished, this embodied energy is lost. Some embodied energy can be saved if parts of the building are recycled and reused.

CHAPTER 4

THERMAL COMFORT

Thermal Comfort—that condition of mind which expresses satisfaction with the thermal environment.
as defined by ASHRAE Standard 55-66

The earth was not given to us by our parents but lent to us by our children.
Kenyan proverb

4.1 BIOLOGICAL MACHINE

The human being is a biological machine that burns food as a fuel and generates heat as a by-product. This metabolic process is very similar to what happens in an automobile, where gasoline is the fuel and heat is a significant by-product (Fig. 4.1a). Both types of machines must be able to dissipate the waste heat in order to prevent overheating (Fig. 4.1b). All of the heat-flow mechanisms mentioned in Chapter 3 are employed to maintain the optimum temperature.

All warm-blooded animals, and humans in particular, require a very constant temperature. The hypothalamus, a part of our brain, regulates our bodies to maintain an interior temperature of about 98.6°F (37°C), and any small deviation creates severe stress. Only 10 to 15 degrees higher or 20 degrees lower can cause death. Our bodies have several mechanisms to regulate heat flow to guarantee that the heat loss equals the heat generated and that the thermal equilibrium will be at about 98.6°F (37°C).

Some heat is lost by exhaling warm, moist air from the lungs, but most of the body's heat flow is through the skin. The skin regulates heat flow partly by controlling the amount of blood flowing through it. In summer the skin is flushed with blood to increase the heat loss, while in winter little blood is allowed to circulate near the surface and the skin becomes an insulator. The skin temperature will, therefore, be much lower in winter than in summer. Skin surface temperatures can vary over 50°F (27°C) in response to the ambient temperature. The skin also contains sweat glands that control body heat loss by evaporation.

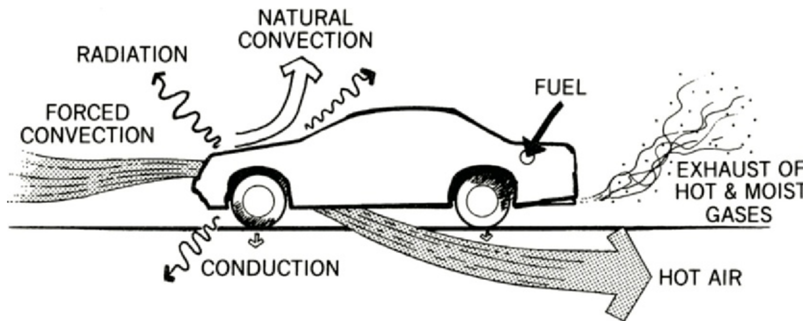


Figure 4.1a Methods of dissipating waste heat from an automobile.

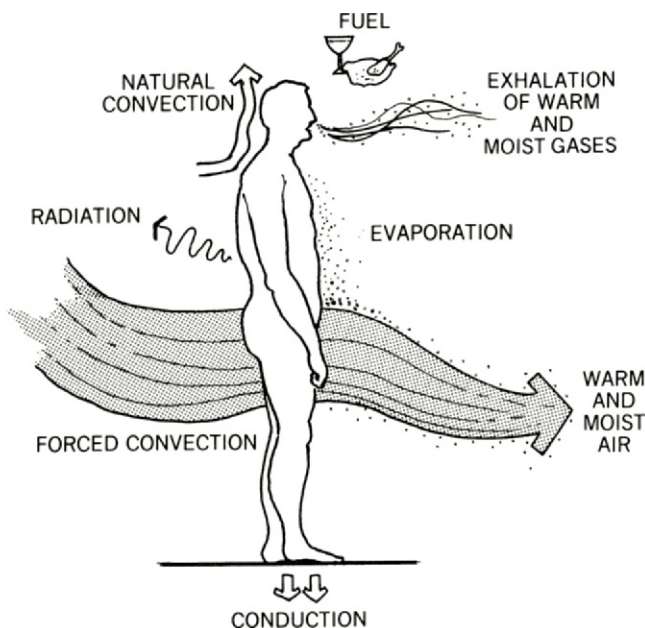


Figure 4.1b Methods of dissipating waste heat from a biological machine.

Hair is another important device to control the rate of heat loss. Although we no longer have much fur, we still have the muscles that could make our fur stand upright for extra thermal insulation. When we get gooseflesh, we see a vestige of the old mechanism. After some days of exposure, the body can acclimatize to very high or low temperatures. Changing the total amount of blood is one important mechanism, with more blood produced under warmer conditions. Excessive heat loss is called hypothermia, while insufficient heat loss is hyperthermia.

The graph in Figure 4.1c shows how the effectiveness of our heat-loss mechanisms varies with the ambient temperature. Curve 1 represents the heat generated by a person at rest as the ambient temperature changes. Curve 2 represents the heat lost by conduction, convection, and radiation. Since the heat loss by these mechanisms depends on the temperature difference, it is not surprising that heat loss decreases as ambient temperature increases. When the ambient temperature reaches the body temperature of 98.6°F (37°C), no heat loss can occur by conduction, convection, and radiation. Fortunately, another heat-loss mechanism is not affected by the ambient temperature. Heat loss by evaporation actually works better at higher temperatures. Curve 3 represents the heat lost by evaporation as the ambient temperature changes with the relative humidity fixed at 45 percent.

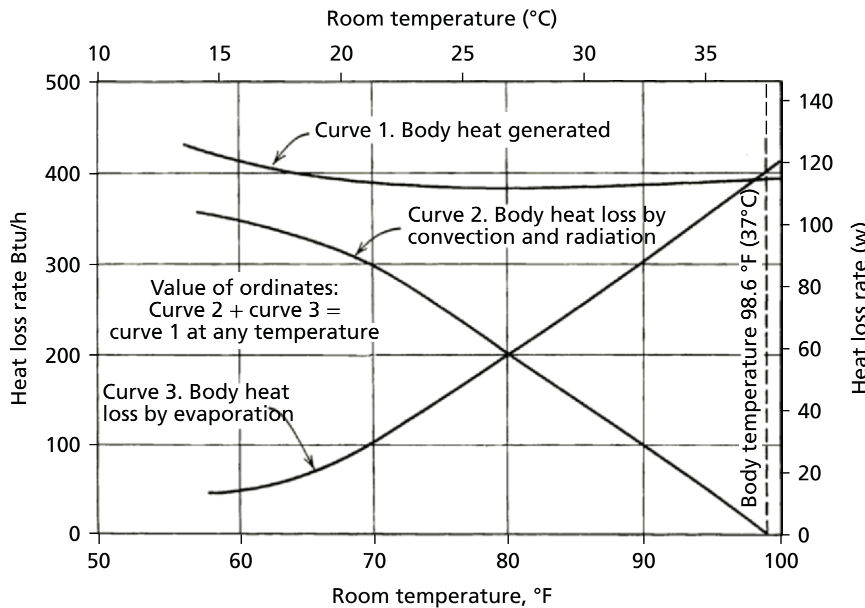


Figure 4.1c The way heat is lost from a body depends on the ambient temperature. This chart assumes the person is at rest and that the relative humidity is 45 percent. (From *Mechanical and Electrical Equipment for Buildings*, 9th ed., Stein and Reynolds, © 2000 John Wiley & Sons, Inc.)

Although the nerve endings in our skin cannot sense humidity very well, they can sense wetness, which is often related to high relative humidity. The nerve endings also do not sense temperature but rather heat flow. Thus metal, with its high conductivity, will feel cooler than wood at the same temperature.

4.2 THERMAL BARRIERS

If we could all live in the Garden of Eden, it would be easy for our body mechanisms to control heat flow. The real world, however, places our bodies under almost constant thermal stress. Any barrier as thin as the skin will have great difficulty maintaining a constant temperature in a widely changing environment. Consequently, additional barriers are needed to achieve thermal comfort. Clothing, though it acts as an extra skin, is not always sufficient for thermal comfort. Buildings provide a milder environment for the clothed human being. In the drafty buildings of previous ages, still more barriers were needed. The canopy bed was one solution (Fig. 4.2a). In modern buildings, we try to re-create the thermal aspects of the Garden of Eden.

This concept of progressive barriers promises to be expanded. There was a serious suggestion, for example, to enclose the new Alaska capitol building in a pneumatic membrane structure and thereby greatly reduce the thermal stress on the building's inside. Pneumatic structures are ideal for this purpose because they can enclose very large areas at reasonable cost. The U.S. Pavilion for Expo 67 in Montreal, Canada, used a different structural system for the same purpose. Figure 4.2b shows the geodesic dome that created a microclimate within which thermally fragile structures were built. Vents and shades were used to control this microclimate (see also Fig. 9.16a).

More modest but quite common are the sheltered streets of our modern enclosed shopping malls, which had their beginnings in such projects as the Galleria Vittorio Emanuele II in Milan, Italy, completed in 1877 (Fig. 4.2c). The Crystal Palace, built for the Great Exhibition of 1851 in London (Fig. 4.2d), was the ancestor of both the Galleria and the modern Expo pavilion mentioned above. With an area of 770,000 ft^2 (71,500 m^2), it created a new microclimate in a large section of Hyde Park.

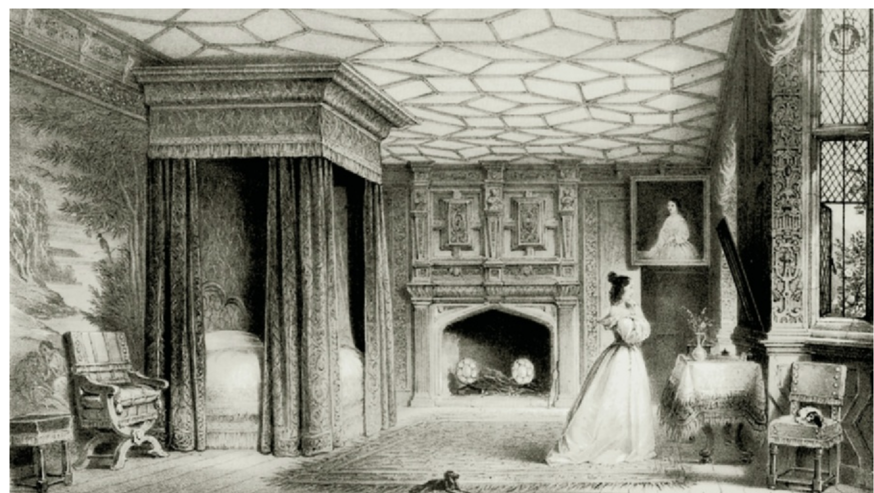


Figure 4.2a The concept of multiple barriers is very appropriate for thermal comfort. Three barriers are shown: clothing, canopy bed, and building. From *Mansions of England in Olden Time* by Joseph Nash.



Figure 4.2b The geodesic dome of the U.S. Pavilion at Expo 67 in Montreal, Canada, protects the interior structures from extreme temperatures, sun, wind, and rain.



Figure 4.2c The Galleria Vittorio Emanuele II, in Milan, Italy, completed 1877, protects both the street and buildings. (Photograph by Clark Lundell.)



Figure 4.2d The Crystal Palace, built for the Great Exhibition of 1851, created a benign microclimate in Hyde Park, London. (Victoria and Albert Museum, London.)

4.3 METABOLIC RATE

To maintain vital thermal equilibrium, our bodies must lose heat at the same rate at which the metabolic rate produces it. This heat production is partly a function of outside temperature but mostly a function of activity. A very active person generates heat at a rate more than eight times that of a reclining person. Table 4.3 shows the heat production related to various activities. For a better intuitive understanding, consider how many 100-watt lamps would be needed to produce the same amount of heat.

Table 4.3 Body Heat Production as a Function of Activity

Activity	Heat Produced (Btu/h)	Heat Produced (Watts)
Sleeping	340	100
Light work	680	200
Walking	1020	300
Jogging	2720	800

Notes:
1. The numbers given are approximate.
2. 1w = 3.412 Btu/h.

4.4 THERMAL CONDITIONS OF THE ENVIRONMENT

To create thermal comfort, we must understand not only the heat dissipation mechanisms of the human body but also the four environmental conditions that allow the heat to be lost.

These four conditions are:

1. Air temperature (°F) (°C)
2. Relative humidity
3. Air movement (feet/minute) (m/s)
4. Mean radiant temperature (MRT)

All of these conditions affect the body simultaneously. Let us first examine how each of these conditions by itself affects the rate of heat loss in human beings.

1. *Air temperature.* The air temperature will determine the rate at which heat is lost to the air, mostly by convection. Above 98.6°F (37°C), the heat flow reverses and the body will gain heat from the air. The comfort range for most people (80 percent) extends from 68°F (20°C) in winter to 78°F (25°C) in summer. The range is this large mostly because warmer clothing is worn in the winter.
2. *Relative humidity.* Evaporation of skin moisture is largely a function of air humidity. Dry air can readily absorb the moisture from the skin, and the resulting rapid evaporation will effectively cool the body. On the other hand, when the relative humidity (RH) reaches 100 percent, the air is holding all the water vapor it can and cooling by evaporation stops. For comfort, the RH should be above 20 percent all year, below 60 percent in the summer, and below 80 percent in the winter. These boundaries are only approximations, because of the many variables involved. However, at very low humidity levels there will be complaints of dry noses, mouths, eyes, and skin and increases in respiratory illnesses. Static electricity and shrinkage of wood are also problems caused by low humidity.

   High humidity not only reduces the evaporative cooling rate but also encourages the formation of skin moisture (sweat), which the body senses as uncomfortable. Furthermore, mildew growth is frequently a serious problem when the humidity is high.
3. *Air movement.* Air movement affects the heat-loss rate by both convection and evaporation. Consequently, air velocity has a very pronounced effect on heat loss. In the summer, it is a great asset and in the winter a liability. The comfortable range is from about 20 to about 60 feet/minute (fpm) (0.1 to 0.3 m/s). From about 60 to about 200 fpm (0.3 to 1 m/s), air motion is noticeable but acceptable depending on the activity being performed. Above 200 fpm (2 mph; 3.2 kph), the air motion can be slightly unpleasant and disruptive (e.g., papers are blown around). A draft is an undesirable local cooling of the human body by air movement, and it is a serious thermal comfort problem. See Table 10.8 for a more detailed description of how air velocity affects comfort. Air motion is also required to prevent excessive stratification, which tends to make heads warmer and feet colder—exactly the opposite of what is comfortable.

   In cold climates, windchill factors are often given on weather reports because they better describe the severity of the cold than temperature alone. The windchill factor is equal to the still-air temperature that would have the same cooling effect on a human being as does the combined effect of the actual temperature and wind speed.

   Although air movement from a breeze is usually desirable in the summer, it is not in very hot and dry climates. If the air is above 98.6°F (37°C), it will heat the skin by convection while it cools by evaporation. The higher the temperature, the less the total cooling effect.
4. *Mean radiant temperature.* When the MRT differs greatly from the air temperature, its effect must be considered. For example, when you sit in front of a south-facing window on a sunny day in the winter, you might actually feel too warm, even though the air temperature is a comfortable 75°F (24°C). This is because the sun's rays raised the MRT to a level too high for comfort. As soon as the sun sets, however, you will probably feel cold even though the air temperature in the room is still 75°F (24°C). This time the cold window glass lowered the MRT too far, and you experience a net radiant loss. It is important to realize that the skin and clothing temperature is not 98.6°F (37°C) but varies greatly with the ambient

temperature. To help visualize the radiant exchange, assume the skin temperature to be about 80°F (27°C). In general, the goal is to maintain the MRT close to the ambient air temperature. In a well-insulated and shaded building, the MRT is usually close to that of the indoor air temperature. Since the mean radiant temperature is not always close to the air temperature and yet has a large impact on comfort, the concept of **operative temperature** was developed. The operative temperature is a combination of the air temperature and the MRT.

The psychrometric chart described in the next section is a powerful tool for understanding how the combination of temperature and humidity affects comfort.

4.5 THE PSYCHROMETRIC CHART

A useful and convenient way to understand some of the interrelationships of the thermal conditions of the environment is by means of the psychrometric chart (Fig. 4.5a). The horizontal axis describes the temperature of the air, the vertical axis describes the actual amount of water vapor in the air, called humidity ratio or specific humidity, and the curved lines describe the relative humidity (RH). The diagram has two boundaries that are absolute limits. The bottom edge describes air that is completely dry (0 percent RH), and the upper curved boundary describes air that is completely saturated with water vapor (100 percent RH). The upper boundary is curved because as air gets warmer, it can hold more water vapor. Even if we know how much water vapor is already in the air, we cannot predict how much more it can hold unless we also know the temperature of the air. The RH is affected by changes in either the amount of moisture or the temperature of the air.

Every point on the psychrometric chart represents a sample of air at a particular temperature and moisture level. Moving vertically up on the chart indicates that moisture is being added to that air sample (Fig. 4.5b), while a downward motion on the chart represents water vapor removal (dehumidification). Movement to the right indicates that the air sample is being heated, and movement to the

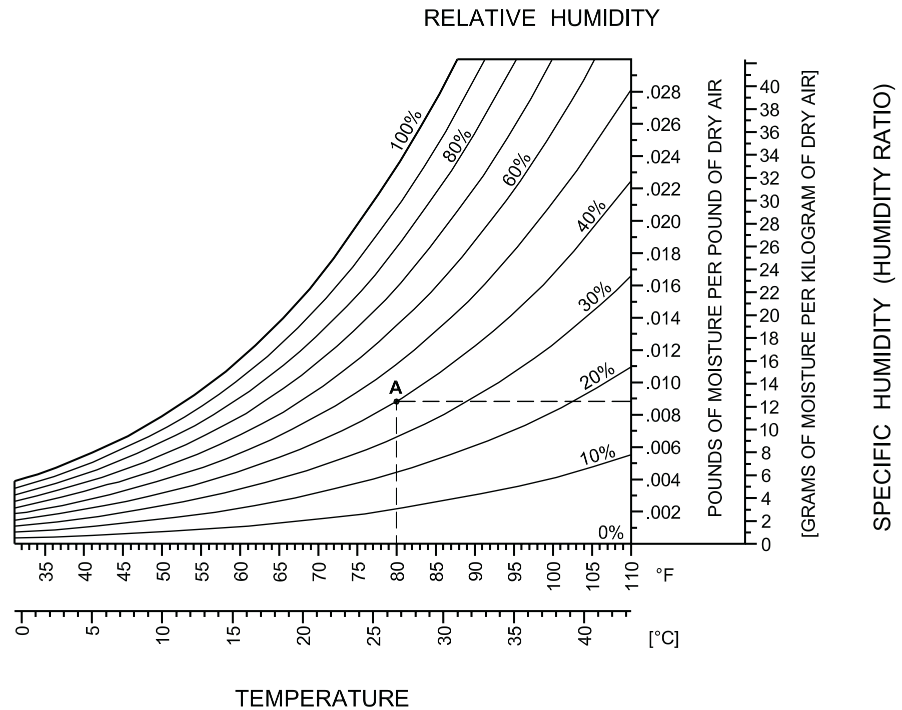


Figure 4.5a Each point on the psychrometric chart represents the properties of a sample of air at a particular temperature and moisture level. At point A, for example, the air sample has a temperature of 80°F (27°C), an RH of 40 percent, and an actual moisture content of about 0.009 lb of water per pound of dry air (12 g of water per kg of dry air).

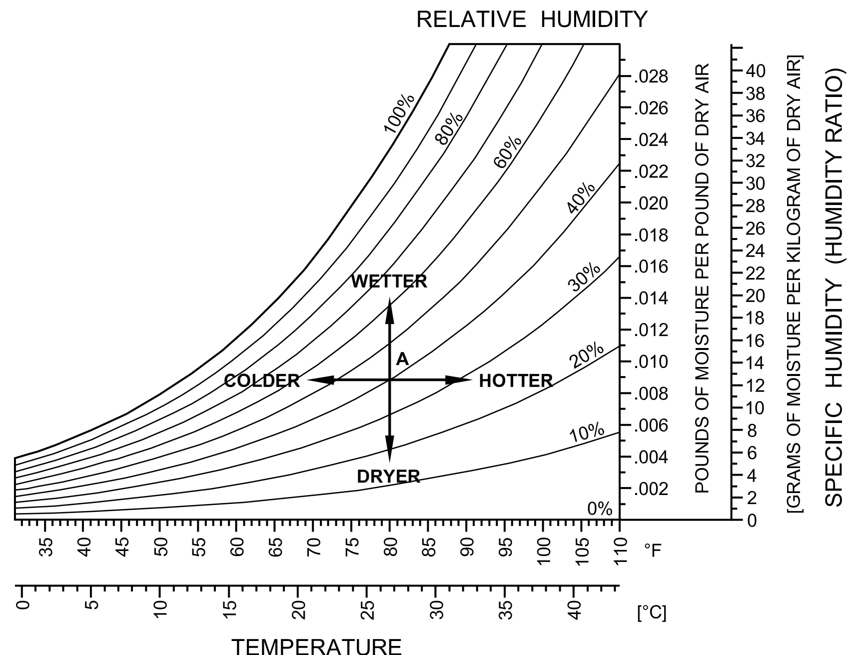


Figure 4.5b Changes in the temperature or moisture of a sample of air are represented by movement on the psychrometric chart.

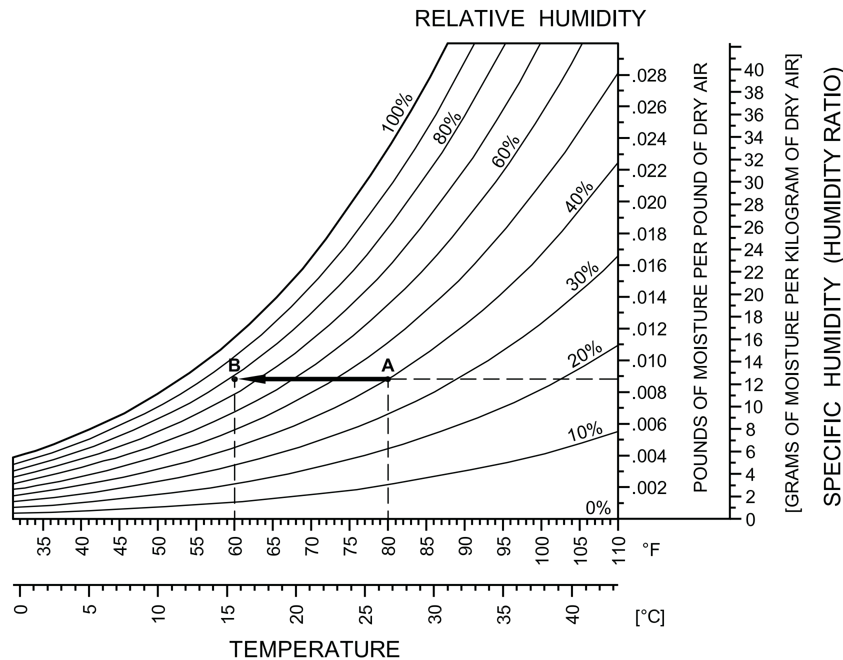


Figure 4.5c If an air sample is cooled, its RH will increase even though there was no change in moisture content.

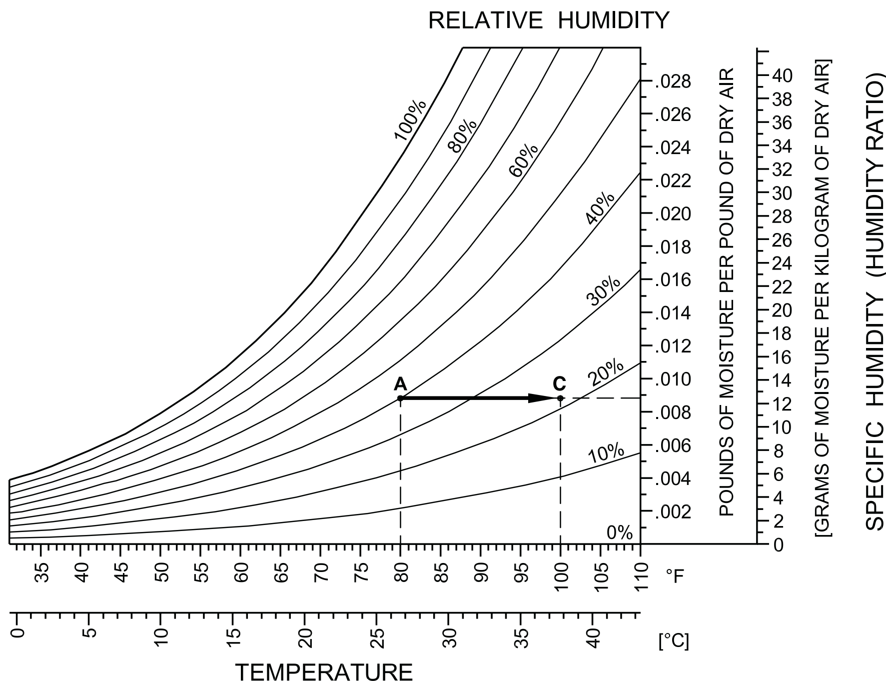


Figure 4.5d If an air sample is heated, its relative humidity will drop even though there was no change in moisture content.

left indicates cooling of the air. Thus, if a sample of air at 80°F (27°C) and 40 percent RH (point A) is cooled to 60°F (15°C), the point representing the air sample will move horizontally to the left on the psychrometric chart to point B in Figure 4.5c. Its RH, however, has increased to about 78 percent even though there was no change in the moisture content of the air (i.e., no vertical movement on the chart). The RH increased because cool air can hold less moisture than warm air, and the existing moisture level is now a larger percentage of what air can hold at that cooler temperature.

On the other hand, if the air at point A is heated to 100°F (38°C) (point C in Fig. 4.5d), then its relative humidity will be about 22 percent. The RH changed because warm air can hold more moisture than cool air, and the existing moisture level is now a smaller percentage of what the air can hold at that higher temperature.

4.6 DEW POINT AND WET-BULB TEMPERATURES

What would happen to air that is at 80°F (27°C) and 40 percent RH (point A in Fig. 4.6a), if it were cooled to 53°F (12°C; point B)? As the air is cooled, the RH keeps increasing until it is 100 percent at about 53°F (12°C) (point D). This is a special condition called the **dew point temperature (DPT)**. At this point the air is fully saturated (100 percent RH) and cannot hold any more moisture. Any cooling beyond this point results in condensation where some of the water comes out of solution in the air as when dew is formed. This phenomenon is also seen in rain, snow, fog, hoarfrost, and the "sweating" of a cold glass of water.

If the above sample of air is cooled beyond 53°F (12°C) to 40°F (4°C), it will reach point E on the psychrometric chart (Fig. 4.6a). Although its RH is still 100 percent, its specific humidity (humidity ratio) has decreased. Note the downward movement on the psychrometric chart from a humidity ratio of about 0.009 to about 0.0055 lb of water per pound of dry air (12 to about 8 g/kg). Consequently, about 0.0035 lb of water per pound of dry air (4 g/kg) was removed from the air when it was cooled from 80°F (27°C) to 40°F (4°C). We can say that the air was dehumidified.

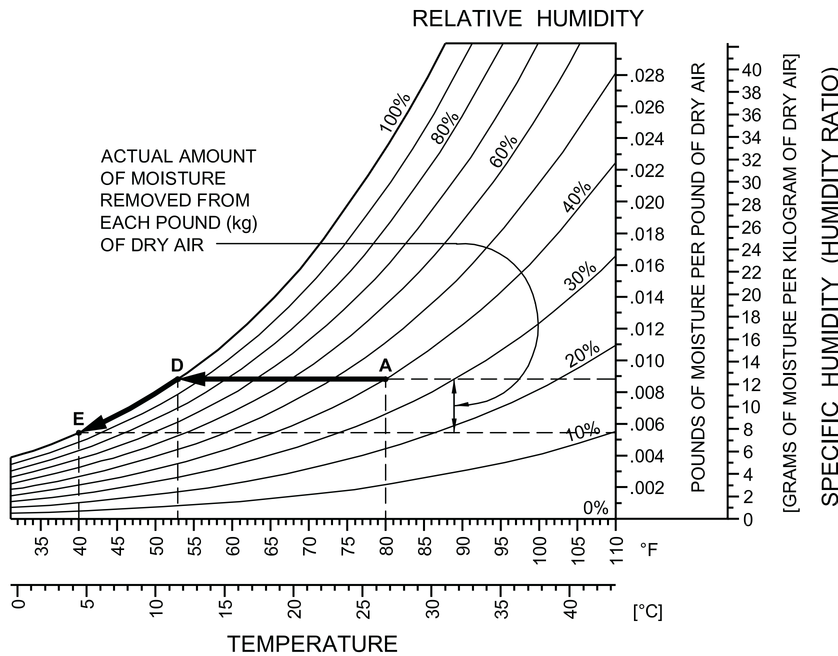


Figure 4.6a When an air sample is cooled sufficiently, its RH increases until is reaches 100 percent, which is also called the saturation or dew point. Any cooling beyond this point results in moisture condensing out of the air.

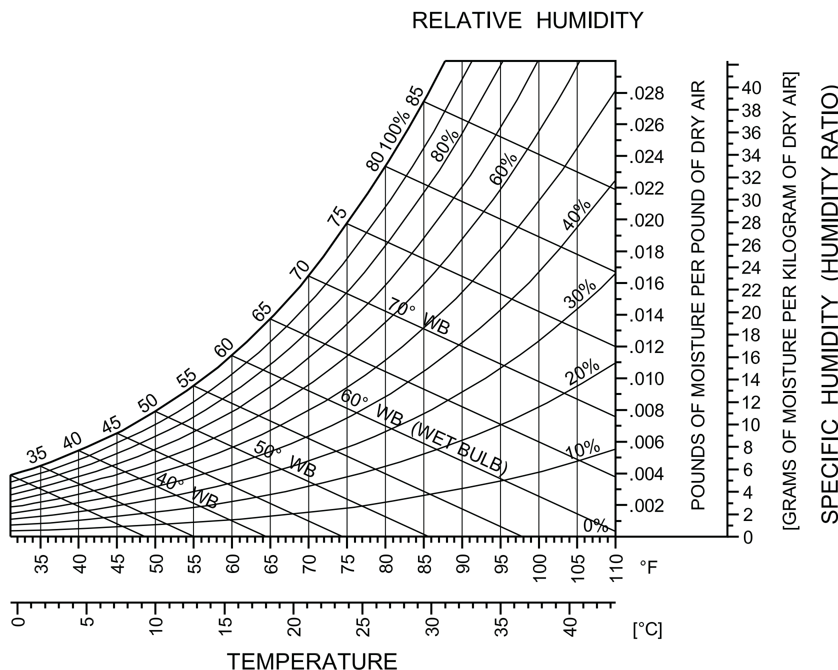


Figure 4.6b The wet-bulb temperature can be measured with a sling psychrometer, and it is an indicator of the RH, the actual moisture content, and the heat content of the air.

The DPT is also an indication of how much moisture is in the air at any temperature. The higher the DPT, the more moisture. Thus, the DPT can be used to describe the actual amount of moisture in the air. Weather reports often give the DPT to describe the moisture content of the air.

Another way to describe the amount of moisture in an air sample is by giving its web-bulb temperature. The wet-bulb temperature is determined by slinging two thermometers side by side through the air. One thermometer has its bulb covered with a wet sock. If this sling psychrometer is slung around in dry air, the temperature of the wet-bulb thermometer will drop significantly below the temperature of the dry-bulb thermometer because of the large evaporation of water. Similarly, if the air is humid, the wet-bulb temperature will drop only a little. And, of course, if the air is at 100 percent RH, no evaporation will take place, and the wet-bulb and dry-bulb temperatures will be the same. Figure 4.6b shows how at 100 percent RH, the wet-bulb temperatures (slanted lines) and the dry-bulb temperatures (vertical lines) are the same.

4.7 HEAT CONTENT OF AIR

The psychrometric chart can also be used to describe the sensible-, latent-, and total-heat content of an air sample. The total-heat or **enthalpy** (sensible plus latent heat) scale is a standard part of the psychrometric chart and is shown in Figure 4.7a. Note that an upward movement on the chart increases not only the moisture content but also the latent-heat content. This is not a surprise if you remember that water vapor is a form of latent heat. Also, note that a movement to the right increases not only temperature but also the sensible-heat content of an air sample. This is also not a surprise because temperature is an indicator of sensible-heat content.

Figure 4.7b shows air that is being both heated and humidified. Thus, when the air reaches point F, it has

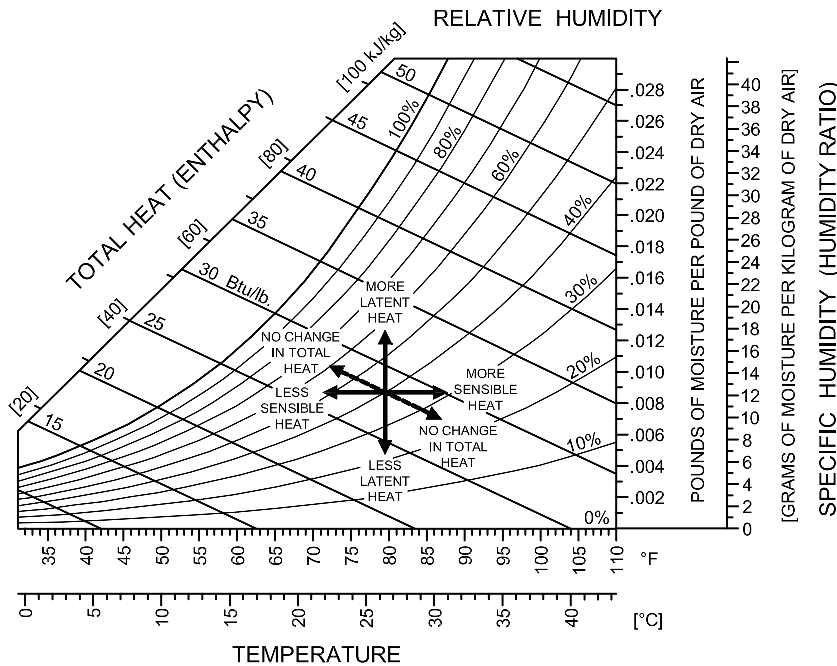


Figure 4.7a The psychrometric chart also presents information on the heat content of a sample of air. Heat is gained by either an increase in temperature (sensible heat) or an increase in moisture (latent heat) or both.

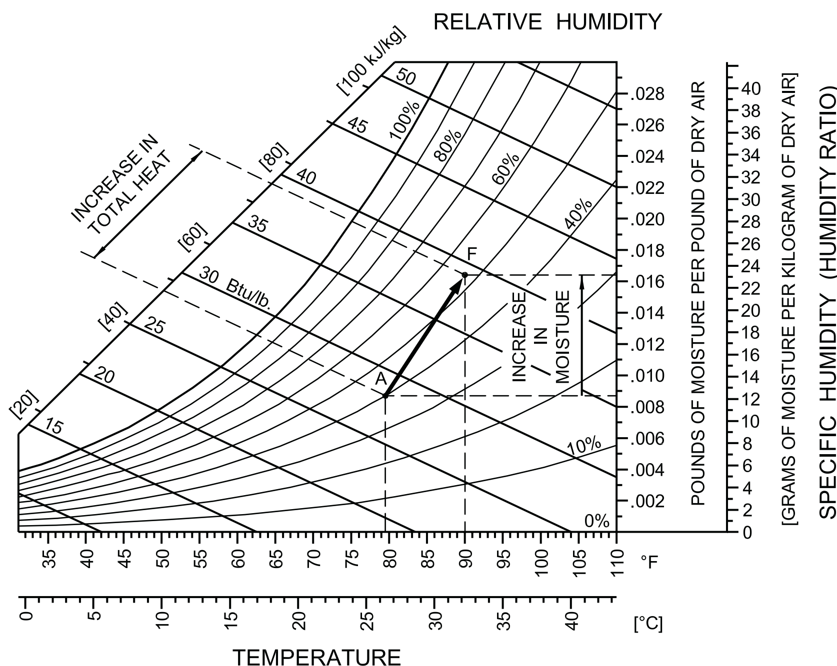


Figure 4.7b Heating and humidifying an air sample increases both its sensible and latent heat. The total-heat gain can be read directly from the enthalpy scale.

both more sensible and more latent heat than it had at point A. The total increase in Btus per pound of dry air (kJ/kg) can be read directly from the enthalpy scale.

In Figure 4.7c, we see a sample of air that is being cooled by the evaporation of water. If the air is humidified to 80 percent RH, the moisture content will increase and the temperature will decrease. Since the loss of sensible heat equals the gain in latent heat, the total-heat content is the same for point G as it was for point A. Note that there is no change on the total-heat scale. A change in the air that does not result in a change of total-heat content is called an **adiabatic** change. This is an important and common phenomenon since this is what happens in evaporative cooling, in which the evaporation of water converts sensible heat to latent heat and the

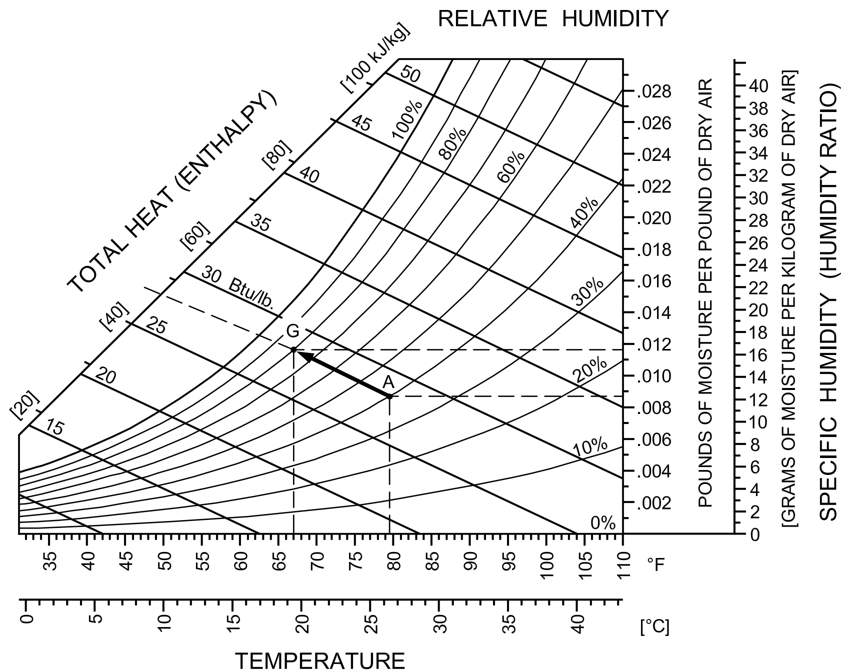


Figure 4.7c In evaporative cooling, the increase in latent heat equals the decrease in sensible heat. An adiabatic change is a change in which the total-heat content of the air remains constant.

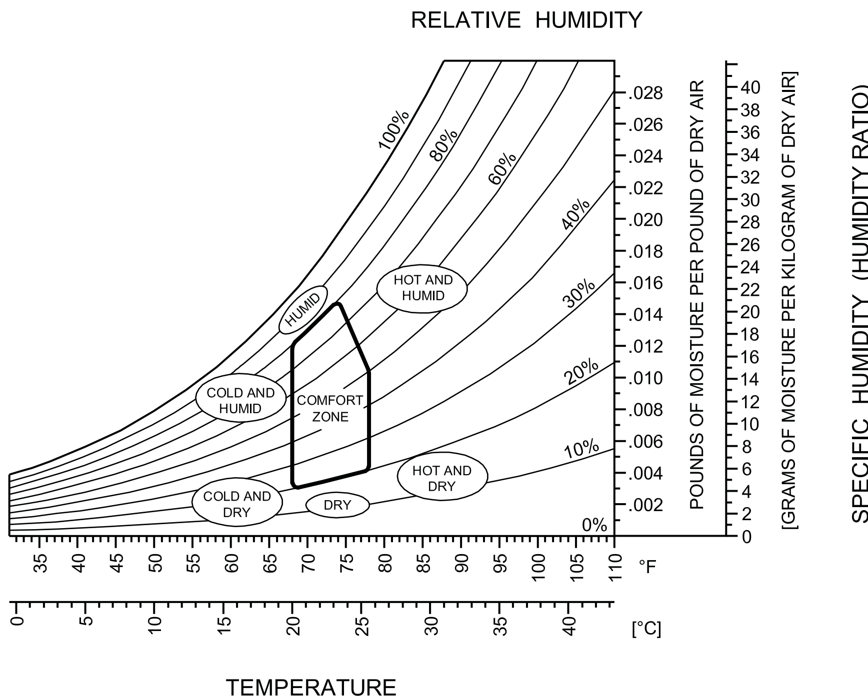


Figure 4.8a The comfort zone and various types of discomfort outside that zone are shown on this psychrometric chart.

total-heat content remains the same. Thus, although the air becomes cooler, it also becomes more humid. It is equally true that when water vapor condenses into water, the temperature rises, since latent heat is being converted to an equal amount of sensible heat.

4.8 THERMAL COMFORT

Thermal comfort occurs when body temperatures are held within narrow ranges, skin moisture is low, and the body's effort at temperature regulation is minimized (after ASHRAE, 1997). Certain combinations of air temperature, RH, air motion, and MRT will result in what most people consider thermal comfort. When combinations of air temperature and RH that are comfortable are plotted on a psychrometric chart, they define an area known as the comfort zone (Fig. 4.8a). Since the psychrometric chart relates only temperature and humidity, the other two factors (air motion and MRT) are held fixed. The MRT is assumed to be near the air temperature, and the air motion is assumed to be modest.

It is important to note that the given boundaries of the comfort zone are not absolute, because thermal comfort also varies with culture, time of year, health, the amount of fat an individual carries, the amount of clothing worn, and, most important, physical activity. The American Society for Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) defines thermal comfort as "that condition of mind which expresses satisfaction with the thermal environment." While conditions required for thermal comfort vary from person to person, the comfort zone should be the goal of the thermal design of a building because it defines those conditions that 80 percent of people in our society find comfortable. A more detailed look at

the comfort zone shows that it consists of both a summer and a winter zone (Fig. 4.8b). For the sake of simplicity, this book continues to use the traditional zone, with the caveat that the left side of the zone is more appropriate for winter and the right side for summer.

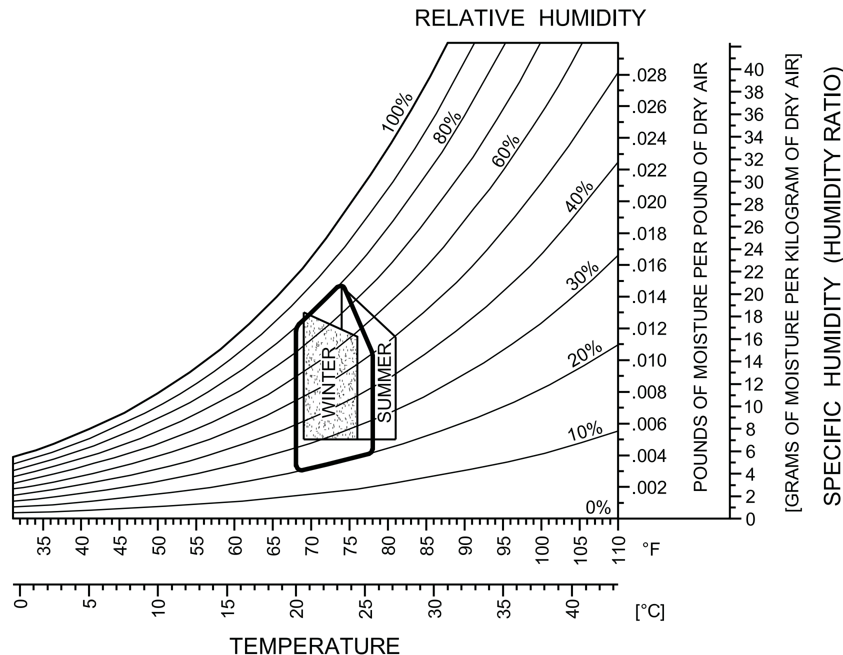


Figure 4.8b A more detailed look at the comfort zone shows that it actually consists of two slightly overlapping zones. (After *ASHRAE Handbook of Fundamentals*, 1997.)

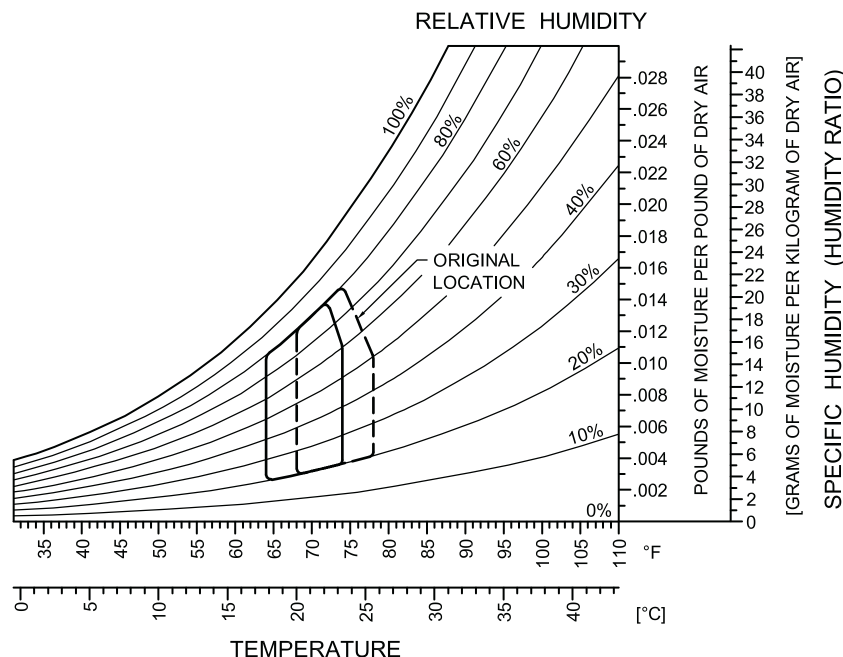


Figure 4.9a To compensate for a high MRT, the comfort zone shifts down to the left.

Whenever possible, additional controls should be made available for the occupants of a building so that they can create the thermal conditions that are just right for them. Portable fans and heaters, numerous thermostats, and operable windows are devices people can use to fine-tune their environment. Mechanical equipment systems are now commercially available that allow individual thermal control at each workstation.

The chart in Figure 4.8a also indicates the type of discomfort one experiences outside of the comfort zone. These discomfort zones correspond to different climates. For example, the American Southwest has a summer climate that is hot and dry, found on the lower right of the psychrometric chart (Fig. 4.8a).

The following discussion shows how the comfort zone shifts when certain variables that had been held constant are allowed to change.

4.9 SHIFTING OF THE COMFORT ZONE

The comfort zone will shift on the psychrometric chart if we change some of the assumptions made above. In Figure 4.9a the shift of the comfort zone is due to an increase in the MRT. Cooler air temperatures are required to compensate for the increased heating from radiation. Likewise, a low MRT would have to be offset by an increase in the air temperature. For example, a room with a large expanse of glass must be kept warmer in the winter and cooler in the summer than a room with a more modest window area. The large window area creates a high MRT in the summer and a low MRT in the winter. For every degree increase or decrease in MRT, the air temperature must be adjusted a degree in the opposite direction. Window shading (Chapter 9) and better-insulated windows (Chapter 15) can have tremendous effects on the MRT.

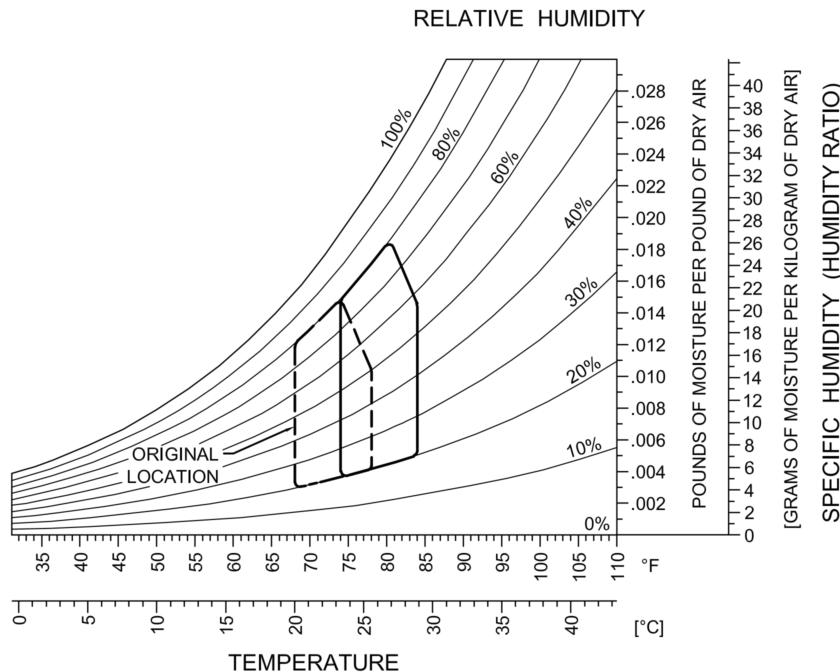


Figure 4.9b To compensate for high air velocity, the cooling effect of air at a high speed, the comfort zone shifts to warmer temperatures (i.e., to the right).

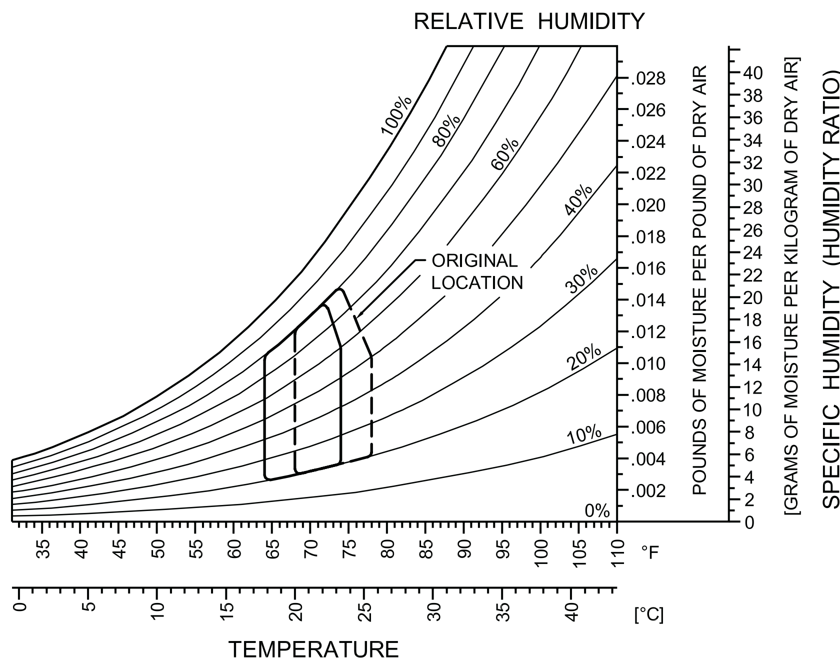


Figure 4.9c To compensate for an increase in physical activity, the comfort zone shifts down to cooler temperatures (i.e., to the left).

In Figure 4.9b the shift of the comfort zone is due to increased air velocity. The cooling effect of the air motion is offset by an increase in the air temperature. We usually make use of this relationship in the reverse situation. When the air temperature is too high for comfort, we often use air motion (i.e., open a window or turn on a fan) to raise the comfort zone so that it includes the higher air temperature. For every increase of 15 fpm (0.8 m/s) of air speed, the comfort zone will shift 1 degree warmer (to the right). Chapter 10 will explain how air movement can be used for passive cooling.

There is also a shift of the comfort zone due to physical activity. Cooler temperatures are required to help the body dissipate the increased production of heat. Gymnasiums, for example, should always be kept significantly cooler than classrooms. Thus, the comfort zone shifts down to the left when physical activity is increased (Fig. 4.9c).

4.10 ADAPTIVE COMFORT

The traditional thermal comfort guidelines described above were developed for the static conditions that are created by an air-conditioning system. However, research has shown that these guidelines are not valid for naturally ventilated buildings where the occupants have some control over their environment, because people can adapt to changes. **Adaptive comfort** occurs in three ways: behavioral, physiological, and psychological.

Behavioral adaptations include such strategies as opening and closing windows and adjusting blinds for more or less sunshading. It also includes wearing appropriate clothing, which is covered in the next section.

Physiological adaptation (acclimatization) includes the body's strategy to pump more or less blood to the skin. More blood, for example, will increase the skin's temperature and thereby increase heat loss. Another adaptation strategy is to regulate the amount of evaporation from the skin, which at high rates is called sweating.

The third method of adaptation is psychological (shifting expectations). People's satisfaction with the thermal environment is heavily influenced by what they expect at a certain location and time. For

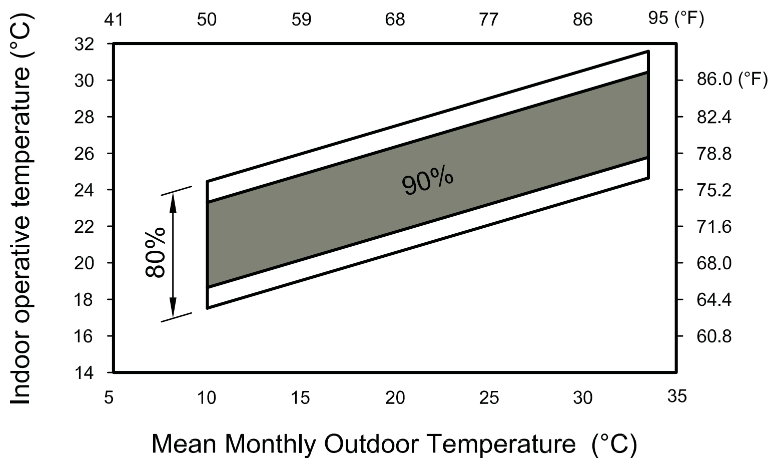


Figure 4.10 Under certain circumstances, people can be comfortable in conditions that fall outside the traditional comfort zone. In naturally ventilated buildings and where occupants have some control over their environment, the adaptive comfort zone increases along with the outdoor temperature. Operative temperature includes both air temperature and MRT.

example, people expect higher indoor temperatures in the summer than in the winter. As a result, what people consider to be comfortable indoor temperatures is related to outdoor temperatures as shown in Figure 4.10, where the indoor comfort zone rises along with the outdoor temperature.

Among the benefits of utilizing adaptive comfort are the reduction of energy consumption and greater comfort for the occupants. Buildings use less energy because the temperature difference between indoors and outdoors is less both summer and winter. Occupants are more comfortable because they have greater control over their thermal environment to meet their individual needs, since there are always some people who want it hotter or cooler.

A building designed for adaptive comfort is both naturally ventilated (i.e., operable windows for part of the year) and under the control of the occupants, who can actively modify their immediate environment hourly, daily, and seasonally, to meet their needs. Interior wall colors and furnishings could be chosen to promote comfort during the dominant season. For example, warm colors (red, orange, and yellow) would be used in cold climates and cool colors (blue and green) in hot climates. The furniture design could support adaptation by having the chair seats and backs made of a well-ventilated open-weave fabric rather than upholstery, making them cooler in the summer. In the winter, cushions could be added to the seats and backs to greatly decrease the heat loss from a large part of the seated body. The concept of adaptive thermal comfort for buildings is supported by the American Society of Heating and Air-Conditioning Engineers (ASHRAE), but no specific guidelines are given for its utilization at this time.

4.11 CLOTHING AND COMFORT

Unfortunately, an architect cannot specify the clothing to be worn by the occupants of his or her building. Too often, fashion, status, and tradition in clothing work against thermal comfort. In some extremely hot climates, women are required to wear black veils and robes that completely cover their bodies. Unfortunately, some North American customs are almost as inappropriate. A three-piece suit with a necktie can get quite hot in the summer. A miniskirt in the winter is just as unsuitable. Clothing styles should be seasonal indoors as well as outdoors so that our heating and cooling systems can work less hard. We could save millions of barrels of oil if men wore three-piece suits only in the winter and women wore miniskirts only in summer. Note to fashion designers: You can help fight global warming.

The insulating properties of clothing have been quantified in the unit of thermal resistance called the **clo**. In winter, a high clo value is achieved by clothing that creates many air spaces, either by multiple layers or by a porous weave. If wind is present, then an outer layer that is fairly airtight but permeable to water vapor is required.

In summer a very low clo value is, of course, required. Since it is even more important in the summer than in the winter that moisture can pass through the clothing, a very permeable fabric should be used. Cotton is especially good because it acts as a wick to transfer moisture from the skin to the air. Although wool is not as good as cotton in absorbing moisture, it is still much better than some man-made materials. Also, loose billowing clothing will promote the dissipation of both sensible and latent heat (water vapor) as air is fanned across the skin.

4.12 STRATEGIES

Much of the rest of this book discusses the various strategies that have been developed to create thermal comfort in our buildings. The version of the psychrometric chart shown in Figure 4.12 is called the **building bioclimatic chart** because it integrates architectural strategies with human comfort needs. If you compare this chart with Figure 4.8a, you will see the relationship between strategies and discomfort (climate) conditions more clearly. For example,

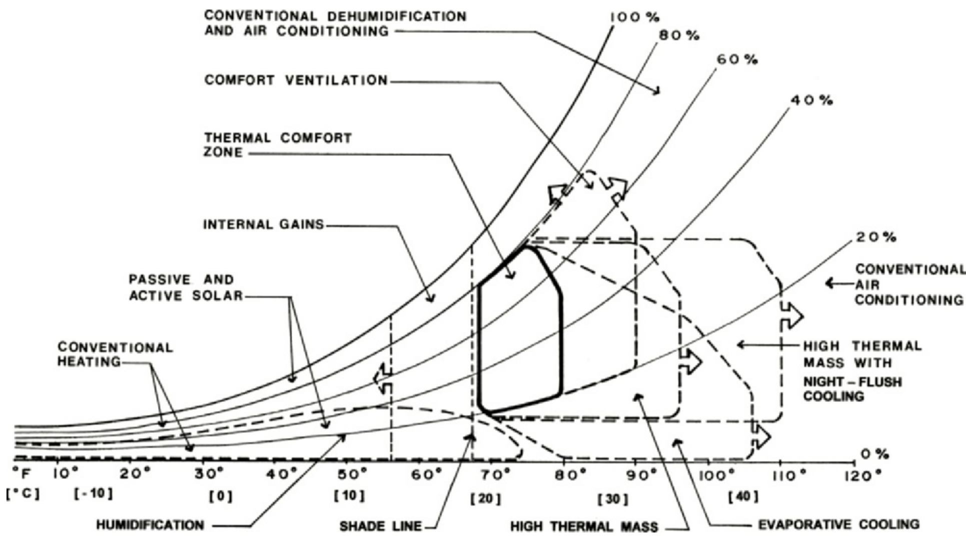


Figure 4.12 This building bioclimatic chart is a summary of design strategies as a function of ambient conditions (climate). (From *Psychrometric-Bioclimatic Chart*, copyright by Baruch Givoni and Murray Milne.)

the strategy of evaporative cooling (the lower-right area in Fig. 4.12) corresponds with the hot and dry discomfort zone (the lower-right area in Fig. 4.8a). The diagram also shows that internal heat gains from sources such as machines, people, and lights are sufficient to heat the building in slightly cool conditions.

Furthermore, when the climate conditions are to the right of the vertical shade line, the sun should be prevented from entering windows. This line, as well as all the boundaries of the various zones shown in the diagram, are not hard and fast but should be considered as approximate limits that vary with building type.

4.13 CONCLUSION

One of the primary functions of buildings is to help create thermal comfort. By understanding human comfort needs and the four conditions of the environment that affect comfort (i.e., temperature, RH, air speed, and MRT), the architect can better design buildings that are comfortable, yet use a minimum of mechanical equipment and little energy. Because climate determines many of the specific architectural strategies that should be used, it is discussed in the next chapter.

KEY IDEAS OF CHAPTER 4

1. For thermal comfort, the body must eliminate waste heat by means of conduction, convection, radiation, and evaporation.
2. The amount of waste heat produced is mostly a function of the physical activity being performed.
3. Four factors of the environment together determine how easily the body can eject the waste heat.
   Their comfort ranges are:
   a. Air temperature: 68° to 78°F (20° to 25°C)
   b. Relative humidity: 20 to 80 percent in the winter and 20 to 60 percent in the summer
   c. Air velocity: 20 to 60 fpm (0.1 to 0.3 m/s)
   d. MRT (near air temperature)
4. Certain combinations of these four factors result in what is called thermal comfort, which can be represented by the comfort zone on charts such as the psychrometric chart.
5. When one or more of the four factors of the environment is somewhat outside its comfort range, the remaining factors can be adjusted up or down to compensate, thereby restoring thermal comfort.
6. The psychrometric chart describes the combined effect of temperature and its coincident humidity.
7. A certain set of temperatures and coincident humidities is called the comfort zone on the psychrometric chart.
8. Recent research on adaptive comfort has shown that the standard comfort zone should be modified for naturally ventilated buildings where the occupants have some control over their immediate environment.
9. The building bioclimatic chart shows which architectural design

strategies are appropriate for different climates, as determined by temperatures and their coincident humidities.

Resources

Further Reading

(See the Bibliography in the back of the book for full citations.)

ASHRAE Handbook of Fundamentals.

Bradshaw, V. *The Building Environment: Active and Passive Control Systems*, 3rd ed.

Brager, G. S., and R. de Dear. *Climate, Comfort, & Natural Ventilation: A New Adaptive Comfort Standard for ASHRAE Standard 55*. 2001.

Flynn, J. E., et al. *Architectural Interior Systems: Lighting, Acoustics. Air Conditioning*, 3rd ed.

Givoni, B. *Climate Considerations in Building and Urban Design*.

———. *Man, Climate and Architecture*, 2nd ed.

Stein, B., J. Reynolds, W. T. Grondzik, and A. G. Kwok. *Mechanical and Electrical Equipment for Buildings*, 10th ed. A general resource.

Organizations

(See Appendix K for full citations.)

American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE).

CHAPTER 5

CLIMATE

What's the use of a fine house if you haven't a tolerable planet to put it on?
Henry David Thoreau

The earth provides enough to satisfy every man's need, but not enough to satisfy every man's greed.
Mahatma Gandhi

We must begin by taking note of the countries and climates in which homes are to be built if our designs for them are to be correct. One type of house seems appropriate for Egypt, another for Spain . . . one still different for Rome. . . . It is obvious that design for homes ought to conform to diversities of climate.
The Ten Books on Architecture, *Vitruvius Architect, first century* B.C.

5.1 INTRODUCTION

As the quote by Vitruvius on the previous page indicates, designing buildings in harmony with their climates is an age-old idea. To design in conformity with climate, the designer needs to understand the microclimate of the site, since all climatic experience of both people and buildings is at this level. In some cases, the microclimate can be quite different from the larger climate.

If Mark Twain were alive today, he would never have said, "Everyone talks about the weather but no one does anything about it." It is now easy to see how man changes the microclimate by such acts as replacing farmland and forest with the hard and massive materials of cities, irrigating a desert and making it a humid area, and constructing high-rise buildings to form windy canyons. Unfortunately, these changes in the microclimate are rarely beneficial, since they are usually done without concern for the consequences.

Most serious, however, are the changes we are making to the macroclimate. As was discussed more fully in Chapter 2, global warming and climate change are mostly caused by the large-scale burning of fossil fuels, which is increasing the amount of carbon dioxide in the air. Carbon dioxide, like water vapor, is transparent to solar energy but not to the long-wave radiation emitted by the earth's surface. Thus, the ground and atmosphere are heated by the phenomenon known as the greenhouse effect. The heating of the earth will create very undesirable changes in the world's climates.

It is too late to stop climate change from starting, but we still have the opportunity to limit the degree of change. Indeed, we have the duty to do everything possible to minimize the amount of change. Climate-responsive buildings are gentle on the climate because they use less energy. However, to design them, we first need to understand the basics of climate.

5.2 CLIMATE

The climate, or average weather, is primarily a function of the sun. The word "climate" comes from the Greek *klima*, which means the slope of the earth in respect to the sun. The Greeks realized that climate is largely a function of sun angles (latitude) and, therefore, they divided the world into the tropic, temperate, and arctic zones.

The atmosphere is a giant heat machine fueled by the sun. Since the atmosphere is largely transparent to solar energy, the main heating of the air occurs at the earth's surface (Fig. 5.2a). As the air is heated, it rises and creates a low-pressure area at ground level. Since the surface of the earth is not heated equally, there will be both relatively low- and high-pressure areas with wind as a consequence.

A global north–south flow of air is generated because the equator is heated more than the poles (Fig. 5.2b). This global flow is modified by both the changes in season and the rotation of the earth (Fig. 5.2c). Another major factor affecting winds and, therefore, climate is the uneven distribution of landmasses

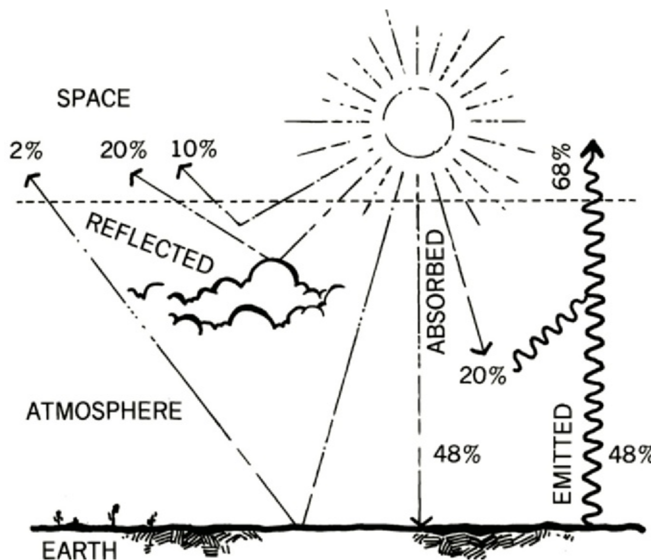


Figure 5.2a The atmosphere is heated mainly by contact with the solar-heated ground. On an annual basis, the energy absorbed by the earth equals the energy radiated back into space. In the summer there is a gain, in the winter an equal loss. This was true until about one hundred years ago, when human-caused global warming started.

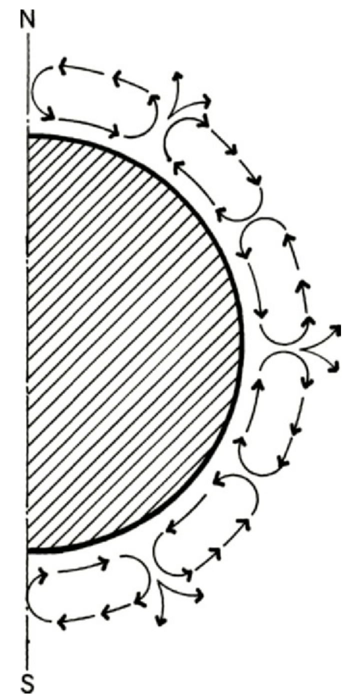


Figure 5.2b Because the earth is heated more at the equator than at the poles, giant global convection currents are generated.



Figure 5.2c The rotation of the earth deflects the north–south air currents by an effect known as the Coriolis force. (From *Wind Power for Farms, Homes and Small Industry*, by the U.S. Department of Energy, 1978.)

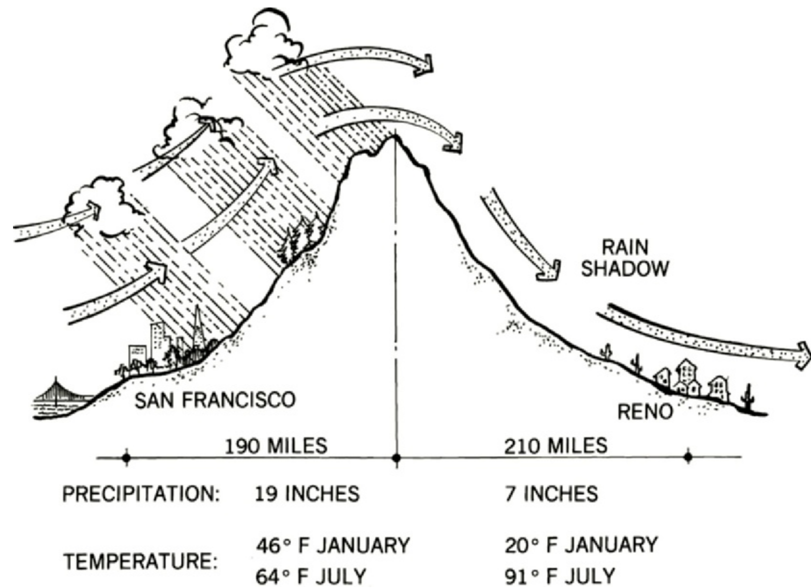


Figure 5.2d In certain cases, mountain ranges cause rapid changes from relatively wet and cool to hot and dry climates. (From *American Buildings: 2: The Environmental Forces That Shape It*, by James Marston Fitch, copyright James Marston Fitch, 1972.)

on the globe. Because of its higher heat capacity and conductivity, the surface of water does not heat up or cool down as fast as the surface of land. Thus, temperature changes over water tend to be more moderate than over land, and the farther inland one gets from large bodies of water, the more extreme are the temperatures. For example, the annual temperature range on the island of Key West, Florida, is about 24°F (13°C), while the annual temperature range inland at San Antonio, Texas, at almost the same latitude, is about 56°F (31°C). These water-land temperature differences also create pressure differences that drive the winds.

Mountain ranges not only block or divert winds but also have a major effect on the moisture content of the air. A good example of this important climatic phenomenon is the American West. Over the Pacific Ocean, solar radiation evaporates water, and the air becomes quite humid. The westerlies blow this moist air overland, where it is forced up over the north–south mountain ranges (Fig. 5.2d). As the air rises, it cools at a rate of about 3.6°F (2°C) for every 1000 ft (300 m). When the temperature drops, the relative humidity (RH) increases until it reaches 100 percent, the saturation point. Any additional cooling will cause moisture to condense in the form of clouds, rain, or snow. On the far side of the mountains, the now drier air falls and, consequently, heats up again. As the temperature increases, the RH decreases and a rain shadow is created. Thus, a mountain ridge can be a sharp border between a cool, wet climate and a hot, dry climate.

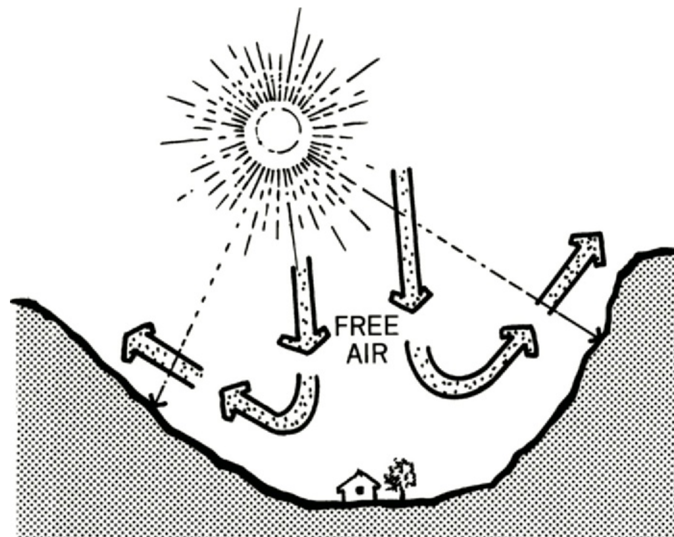


Figure 5.2e During the day, the air moves up the mountainsides.

Mountains also create local winds that vary from day to night. During the day, the air next to the mountain surface heats up faster than free air at the same height. Thus, warm air moves up along the slopes during the day (Fig. 5.2e). At night, the process is reversed: the air moves down the slopes because the mountain surface cools by radiation more quickly than the free air (Fig. 5.2f). In narrow valleys, this phenomenon can create very

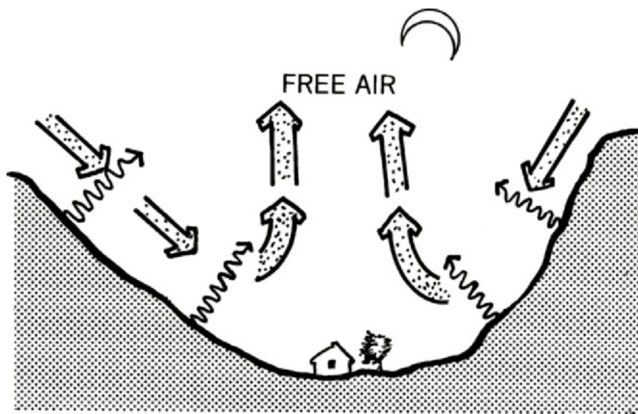


Figure 5.2f At night, the land cools rapidly by radiation, and the air currents move down the mountainsides.

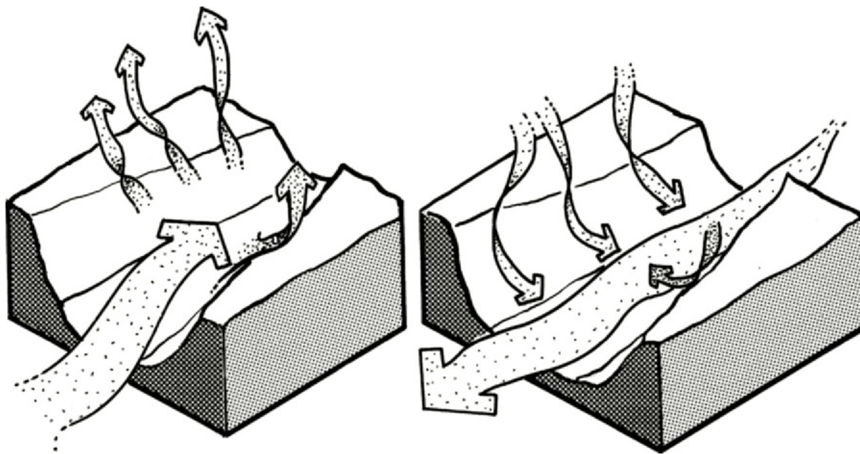


Figure 5.2g The effects described in Figures 5.2e and 5.2f are greatly magnified in narrow-sloping valleys. During the day, strong winds blow up the valley; at night, the winds reverse. (After *Sun, Wind, and Light*, 2nd ed., by G. Z. Brown, and M. DeKay, John Wiley & Sons, 2000.)

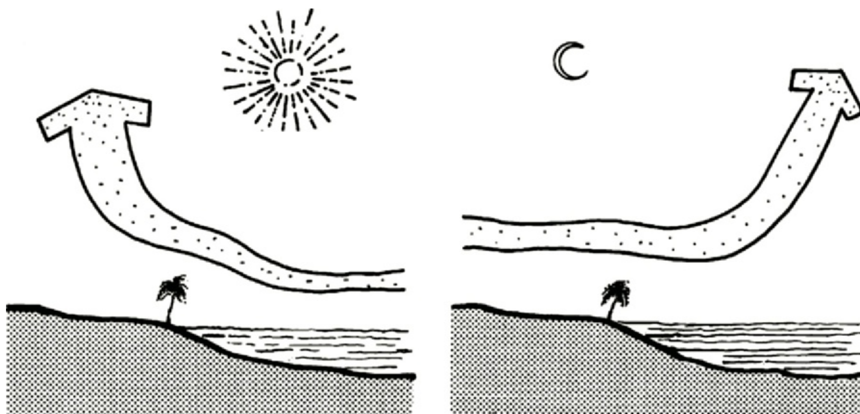


Figure 5.2h The temperature differences between land and water create sea breezes during the day and land breezes at night.

strong winds up along the valley floor during the day and down the valley at night (Fig. 5.2g).

A similar day–night reversal of winds occurs near large bodies of water. The large heat capacity and conductivity of water prevents it from heating or cooling as fast as land. Thus, during the day the air is hotter over land than over water. The resultant pressure differences generate sea breezes (Fig. 5.2h). At night, the temperatures and air flows reverse. In the late afternoon and early morning, when the land and sea are at the same temperature, there is no breeze. Furthermore, at night the breezes are weaker than during the day because the temperature differences between land and water are smaller.

The amount of moisture in the air has a pronounced effect on the ambient temperature. In dry climates, there is little moisture to block the intense solar radiation from reaching the ground, and, thus, summer daytime temperatures are very high—over 100°F (38°C). Also, at night there is little moisture to block the outgoing long-wave radiation; consequently, nights are cool and the diurnal temperature range is high—more than 30°F (17°C) (Fig. 5.2i). On the other hand, in humid and especially cloudy regions, the moisture blocks some solar radiation to make summer daytime temperatures much more moderate—below 90°F (32°C). At night, the outgoing long-wave radiation is also blocked by the moisture, and consequently, temperatures do not drop much (Fig. 5.2j). The diurnal temperature range is, therefore, small—below 20°F (11°C). It should be noted that water has a much stronger blocking effect on radiation when it is in the form of droplets (clouds) than in the form of a gas (humidity).

The various forces in the atmosphere interact to form a large set of diverse climates. Later in the chapter there will be a description of seventeen different climate regions found in the United States and Canada.

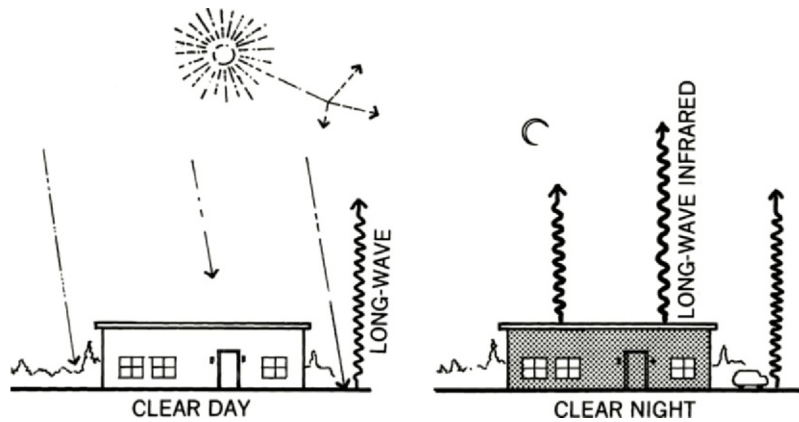


Figure 5.2i Since dry climates have little moisture to block radiation, daytime temperatures are high and nighttime temperatures are low. The diurnal temperature range is, therefore, large.

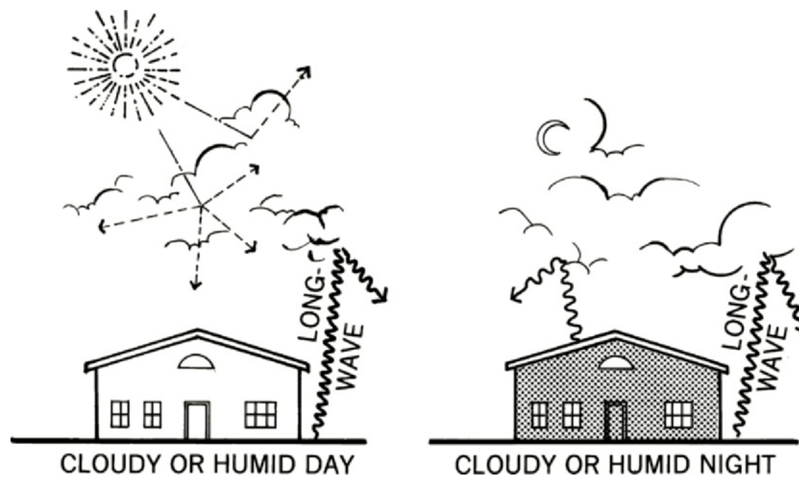


Figure 5.2j Water in the form of humidity and especially in the form of clouds blocks both solar and long-wave radiation. Thus, in humid or cloudy climates, daytime temperatures are not as high and nighttime temperatures are not as low as in hot and dry climates. The diurnal range is, therefore, small.



Figure 5.3a The north side (south slope) of this east–west road is several weeks further into spring than the south side (north slope), where the snow melts much more slowly.

5.3 MICROCLIMATE

For a number of reasons, the local climate can be quite different from the climate region in which it is found. If buildings are to relate properly to their environment, they must be designed for the microclimate in which they exist. The following are the main factors responsible for making the microclimate deviate from the macroclimate:

1. *Elevation above sea level.* The steeper the slope of the land, the faster the temperature will drop with an increase in elevation. The limit, of course, is a vertical ascent, which will produce a cooling rate of about 3.6°F (2°C) per 1000 ft (300 m).
2. *Form of land.* South-facing slopes are much warmer than north-facing slopes because they receive much more solar radiation (Fig. 5.3a). For this reason, ski slopes are usually found on the north slopes of mountains, while vineyards are located on the south slopes (Fig. 5.3b). South slopes are also protected from the cold winter winds that usually come from the north. West slopes are warmer than east slopes because the period of high solar radiation coincides with the high ambient air temperatures of the afternoon. Low areas tend to collect pools of cold, heavy air (Fig. 5.3c). If the air is also moist, fog will frequently form. The fog, in turn, reflects the solar radiation, so these areas remain cool longer in the morning.
3. *Size, shape, and proximity of bodies of water.* As mentioned before, large bodies of water have a significant moderating effect on temperature, they generate the daily alternating land and sea breezes, and they increase the humidity.
4. *Soil types.* The heat capacity, color, and water content of soil can have a significant effect on the microclimate. Evaporation from the soil

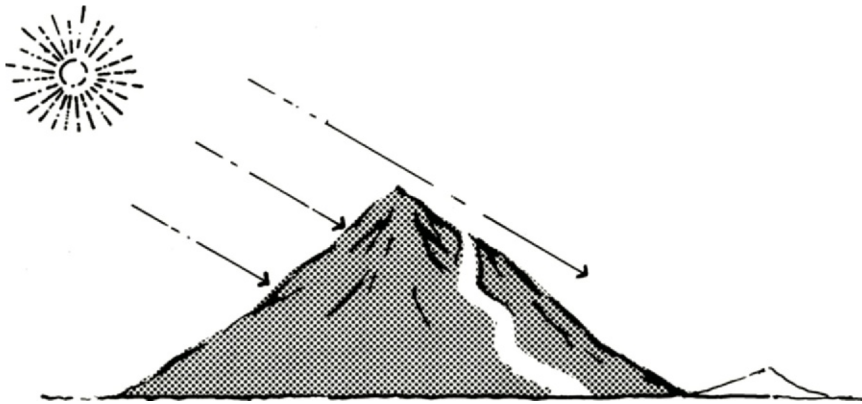


Figure 5.3b South-facing slopes can receive more than one hundred times as much solar radiation as north-facing slopes.

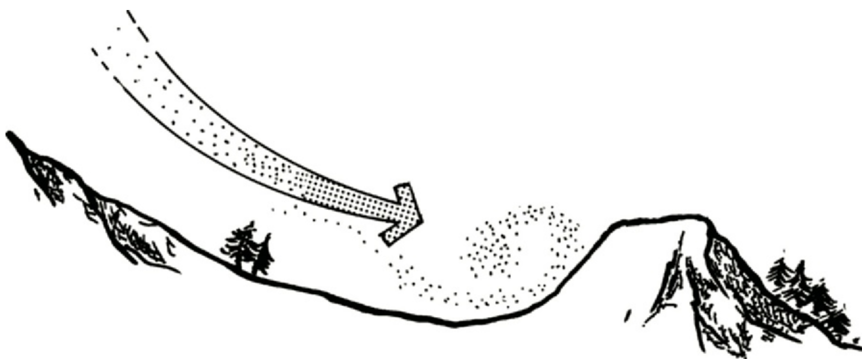


Figure 5.3c Since cool air is heavier than warm air, it drains into low-lying areas, forming pools of cold air.

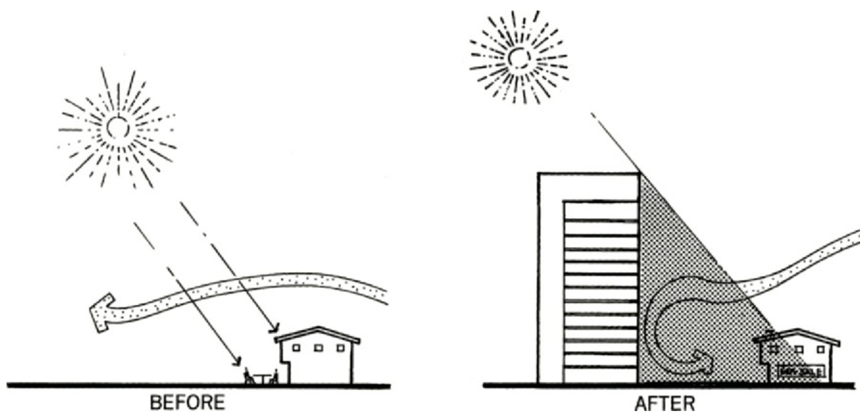


Figure 5.3d A delightfully sunny and wind-protected southern exposure can be turned into a cold, windy microclimate by the construction of a large building to the south.

cools the air above the ground. The surface layer of sand, even though light colored, will get very hot because the absorbed heat cannot easily conduct to lower layers. In addition, the sand will reflect much of the solar radiation thereby greatly increasing the radiant cooling load for people and buildings. Because of their high heat capacity, rocks can absorb heat during the day and then release it at night. The cliff dwellings of the Southwest benefited greatly from this effect (see Fig. 10.2j).

5. *Vegetation.* By means of shading and transpiration, plants can significantly reduce air and ground temperatures. They also increase the humidity, whether or not it is already too high. **Evapotranspiration** is the combined effect of evaporation from soil and transpiration from plants. In a hot, humid climate, the ideal situation is to have a high canopy of trees for shade but no low plants that could block the breeze. The stagnant air created by low trees and shrubs will cause the humidity to build up to undesirably high levels. In cold climates, plants can reduce the cooling effect of the wind by blocking it. Vegetation can also reduce noise and clean the air of dust and certain other pollutants.
6. *Man-made structures.* Buildings, streets, and parking lots, because of their number, size, mass, and color, have a very significant effect on the microclimate. The shade of buildings can create a cold north-like orientation on what was previously a warm southern exposure (Fig. 5.3d). Buildings can also create shade from the hot summer sun and block the cold winter winds. Large areas of pavement, especially dark-colored asphalt, can generate temperatures as high as 140°F (60°C). The heated air then migrates to overheat adjacent areas as well.

In large cities, the combined effect of all the man-made structures results in a climate significantly different from that of the surrounding countryside. The annual mean temperature will usually be about 1.5°F (0.8°C) warmer, while the winter minimum temperature may be about 3°F (1.7°C) higher. In summer, cities can be 7°F (4°C) warmer

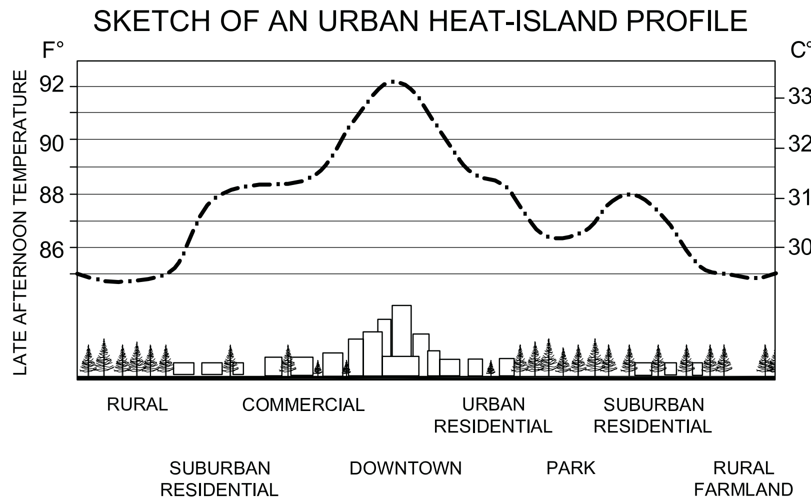


Figure 5.3e A sketch of a typical urban heat-island profile. This profile of a hypothetical metropolitan area shows temperature changes correlated to the density of development and trees. (Reproduced from *Cooling Our Communities: A Guidebook on Tree Planting and Light-Colored Surfacing*, LBL-31587, published by Lawrence Berkeley National Laboratory, 1992.)

than rural areas and are, therefore, often known as heat islands (Fig. 5.3e). Solar radiation, however, will be about 20 percent lower because of air pollution, and the RH will be about 6 percent less because of the reduced amount of evapotranspiration. Although the overall wind speed is about 25 percent lower, very high local wind speeds often occur in the urban canyons. Yet when there is little wind, urban canyons can become very hot due to all the air conditioners pumping heat from indoors to the outdoors.

Buildings should be designed for the microclimate, because the microclimate can be quite different!

5.4 CLIMATIC ANOMALIES

Climates that are radically different from what their location would suggest are called climate anomalies. One of the most famous examples is found in Lugano, Switzerland. Although Lugano has the same latitude as Quebec (47°), the climates are as different as if Lugano were 1500 mi (2400 km) farther south.

This unusually warm climate in a northern region is largely a result of the unique geography of the area. Lugano is located where the southern slope of the Alps meets a large lake (Fig. 5.4). It is thus fully exposed to both the direct winter sun and the sunlight reflected off the lake. The water also has a moderating effect on sudden temperature changes. The Alps protect the area from cold and wet winter winds. Those winds that do get across the Alps are dried and heated, just as are the winds crossing the Sierra Nevada in California (see Fig. 5.2d). And, lastly, the climate in Lugano is unusually warm because of the low elevation of the land. Cold alpine climates are only a few miles away up in the mountains.

Less dramatic variations in the microclimates of a region are quite common. It is not unusual to find in rather flat country that two areas only a few miles apart have temperature differences as great as 30°F (17°C). Suburban areas are often more than 7°F (4°C) cooler during the day and more than 10°F (5.6°C) cooler at night than urban areas. Even a distance of only 100 ft (30 m) can make a significant difference. The author has noted very dramatic temperature differences on his half-acre lot. Consequently, he relaxes in one part of the garden in the summer and in a different part in the cooler seasons.

Very localized variations in the microclimate are especially obvious in the spring. When the snow melts, it does so in irregular patches. The warm areas are also the first to see the green growth of spring. In effect, spring has come several weeks earlier for such areas. These variations are not hard to understand when one considers the fact that in New York on December 21 a south wall receives 108 times as much solar radiation as a north wall. A designer must not only know the climate of the region but also the specific microclimate of the building site.

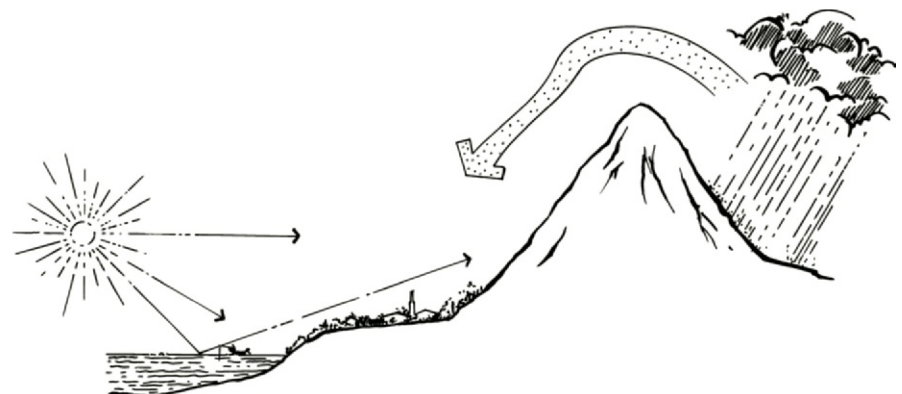


Figure 5.4 The combination of a low elevation, south-facing slopes, high mountains to the north, and a large lake to the south creates a subtropical climate in Lugano, Switzerland, even though it is as far north as Quebec.

Since buildings designed for their climate will use less energy, they will also reduce the amount of global warming. Although climate-responsive design has always been the appropriate design approach, it is fast becoming the mandatory approach.

For a building to be sustainable it must be responsive to its climate!

5.5 CLIMATE REGIONS OF THE UNITED STATES AND CANADA

No book could ever describe all of the microclimates found in the United States. Designers must, therefore, use the best available published data and modify it to fit their specific site. The United States government collects and publishes extensive weather and climatic data. See the end of this chapter for information about some of these resources. However, since the information is usually not arranged in a convenient form for architects to use, some appropriate climate data in a useful graphic format is included in this book.

When the United States is divided into only a few climate regions, the information is too general to be very useful. On the other hand, when too much information is presented, it often becomes inaccessible. As a compromise, this book divides the United States and Canada into seventeen climate regions (Fig. 5.5). This subdivision system and much of the climatic information are based on material from the book *Regional Guidelines for Building Passive Energy Conserving Homes* produced by the AIA Research Corporation.

The remainder of this chapter describes these seventeen climate regions. Included with the climate data for each region is a set of specific climate-related design priorities appropriate for envelope-dominated buildings, such as homes and small institutional and commercial buildings. Specific design strategies that respond to those climatic design priorities are given at the end of the chapter (see Section 5.10).

Some words of caution are very important here. The following climatic data should be used only as a starting point. As much as possible, corrections should be made to account for local microclimates. For building sites near the border between regions, the climatic data for the two regions should be interpolated. The borders should be considered as fuzzy lines rather than the sharp demarcation lines shown in Figure 5.5.

Furthermore, the climate described for each region is the climate for the reference city of that region. Thus, the climate will change with distance from that city, and in large regions that change can be significant. Furthermore, there can also be a large change in latitude.

Because of the Web, it is now possible to easily obtain climate information about more specific locations.

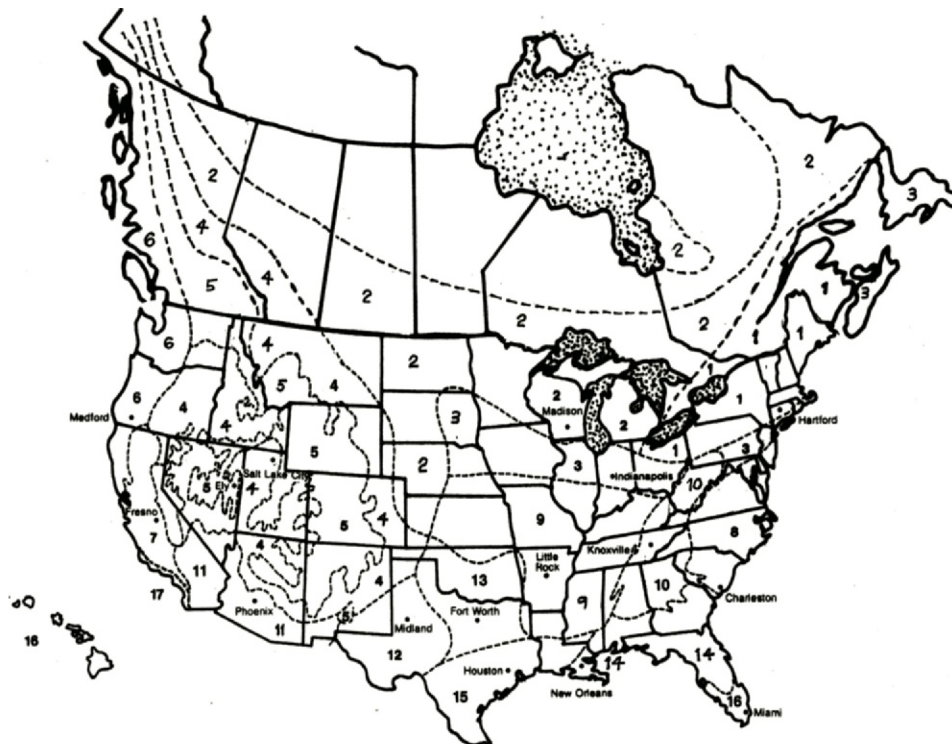


Figure 5.5 This map shows how the United States and Canada are divided into the seventeen climate regions used in this book. A description of each climate region can be found in the Climate Data Tables that follow.

In the United States, look at www.cdc.noaa.gov/usclimate and www.wcc.nrcs.usda.gov/climate. In Canada, see www.climate.weatheroffice.ec.gc.ca. For the rest of the world, see www.worldclimate.com

5.6 EXPLANATIONS OF THE CLIMATIC DATA TABLES

Each of the seventeen climatic regions is described by a climatic data table consisting of two facing pages (Fig. 5.6a), and each part marked with a circled uppercase letter is described below.

A. *Sketch:* The drawing is a representative example of a traditional residential building appropriate for that particular climate region.
B. *Climate region:* The climate of the region is represented by the climatic data for the reference city. The darkened portion of the map represents the particular region for which the data are given.
C. *The climate:* This section of the Climate Data Table provides a verbal description of the climate.
D. *The building bioclimatic chart:* This chart defines the climate in relationship to thermal comfort and the design strategies required to create thermal comfort. See Section 4.12 for an explanation of the building bioclimatic chart.

   The climate of the particular region is presented on this chart by means of twelve straight lines, each of which represents the temperature and humidity conditions for one month of the year. Each line is generated by plotting the monthly normal daily maximum and minimum temperatures with their corresponding RH values. The line connecting these two points is assumed to represent the typical temperature and humidity conditions of that month (Fig. 5.6b). The area or zone defined by the twelve monthly lines represents the annual climate of that region.

   This method of presenting the climate has several advantages. It graphically defines in one diagram both temperature and coincident humidity for each month of the year. This is important because thermal comfort is a function of their combined effect. It shows how severe or mild the climate is by the relationship of the twelve lines to the comfort zone. It also shows which design strategies are appropriate for the particular climate. For example, the chart for

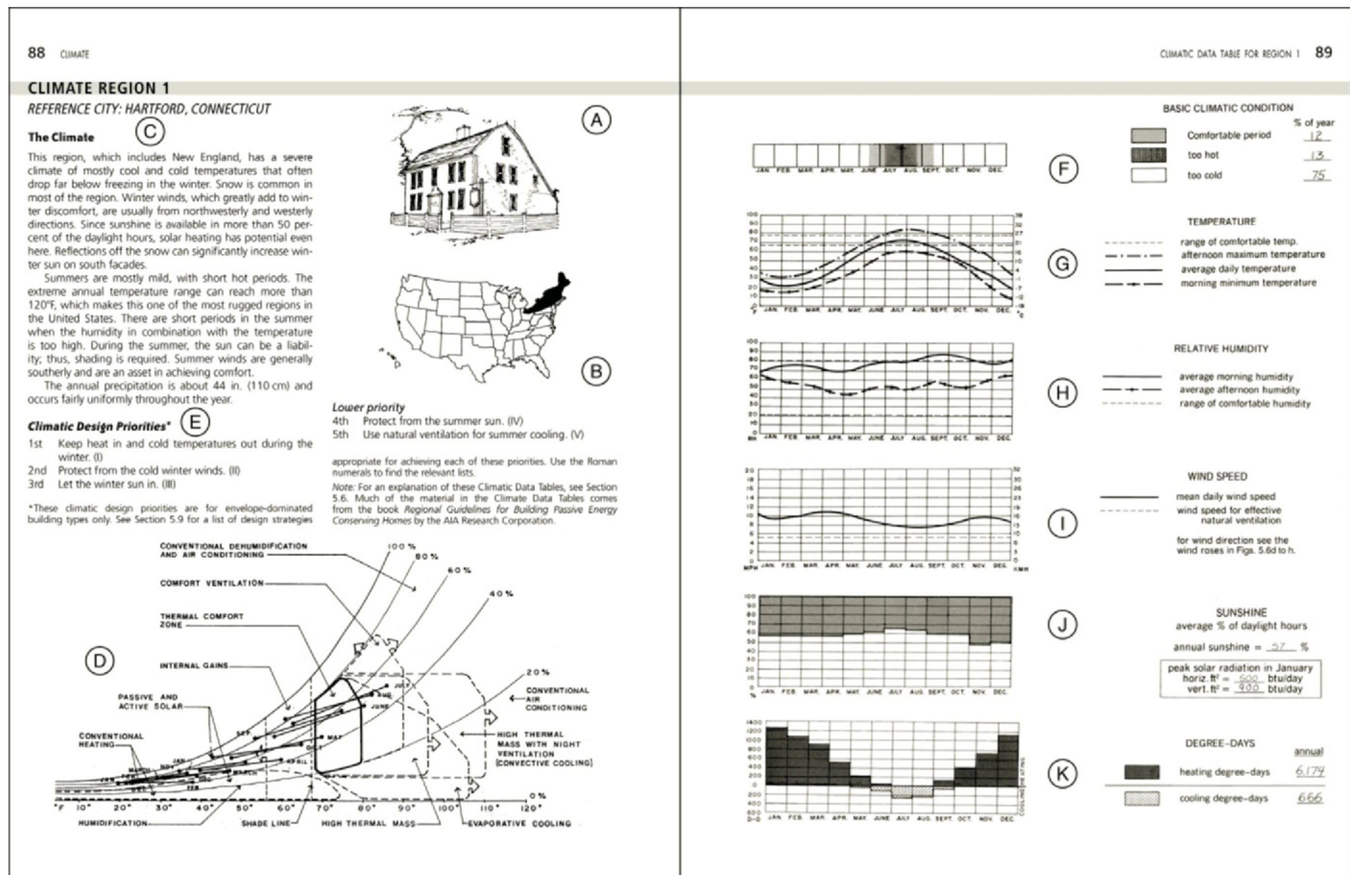


Figure 5.6a This key to the Climatic Data Tables shows how each climate is described on two facing pages.

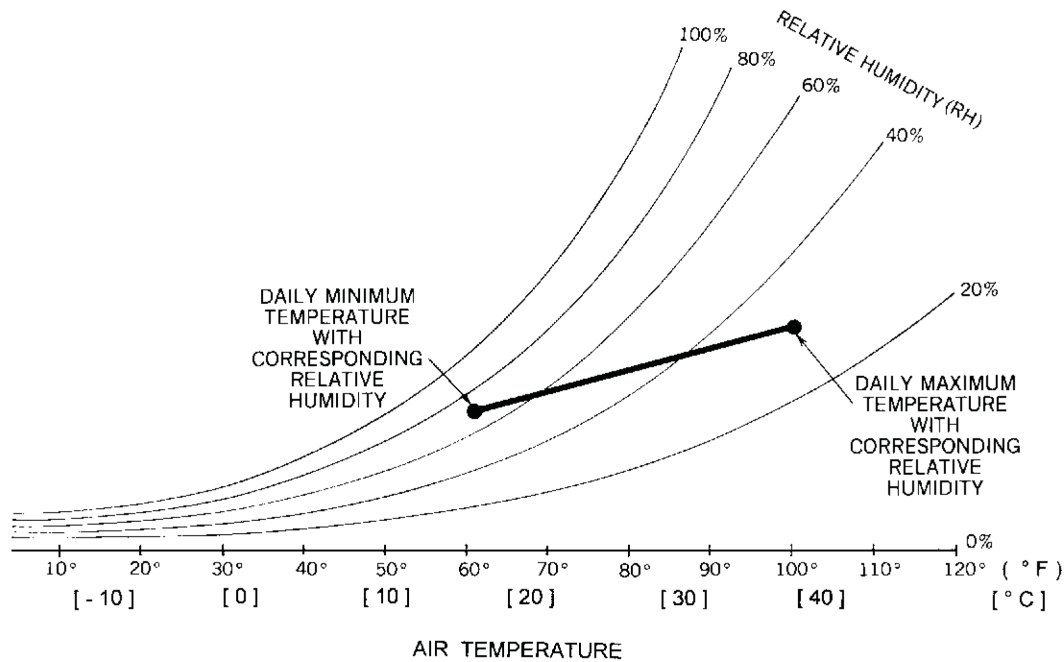


Figure 5.6b On the building bioclimatic chart the climate of a region for any one month is represented by a line.

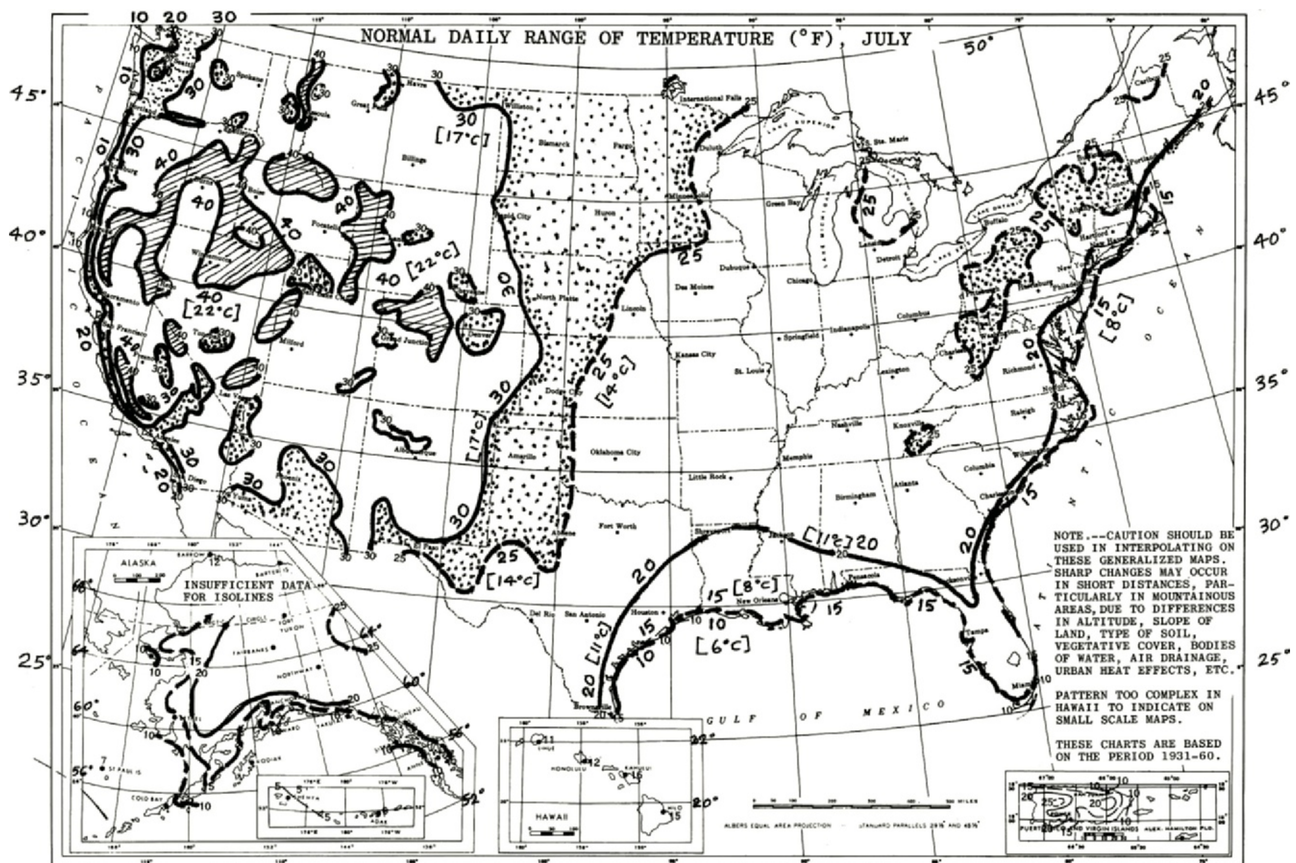


Figure 5.6c July normal daily temperature ranges. (From *Climate Atlas of the U.S.*, National Oceanic and Atmospheric Administration (NOAA) 1983.)

Climate 7 (Fresno, California) indicates a hot and dry summer climate for which evaporative cooling is an appropriate strategy (see p. 108).

E. *Climatic design priorities:* For each climate region, a set of design priorities is given for envelope-dominated buildings, such as residences and small office buildings. Internally dominated buildings, such as large office buildings, are less affected by climate and have much smaller heating and much greater cooling needs. They usually also have a greater need for daylighting. Consequently, these priorities are not directly applicable for internally dominated building types.

The priorities are listed in descending order of importance. The designer should start with the first priority and include as many of the rest as possible. Note that the words “summer” and “winter” are used to refer to the overheated and underheated periods of the year and not necessarily to the calendar months.

F. *Basic climate condition:* This chart shows the periods of the year when the combined effect of temperature and humidity makes the climate either too hot, too cold, or just comfortable. The chart offers a quick answer to the question of what the main thrust of the building design should be: whether the design should respond to a climate that is mainly too hot, too cold, both too hot and too cold, or mostly comfortable.

G. *Temperature:* The temperatures given are averages over many years. Although occasional temperatures are much higher and lower than the averages shown, most designs are based on normal patterns rather than unusual conditions. The vertical distance between the afternoon maximum and morning minimum temperatures represents the diurnal (daily) temperature range. The horizontal dashed lines define the comfort zone.

Daily temperature ranges can also be obtained from the map of

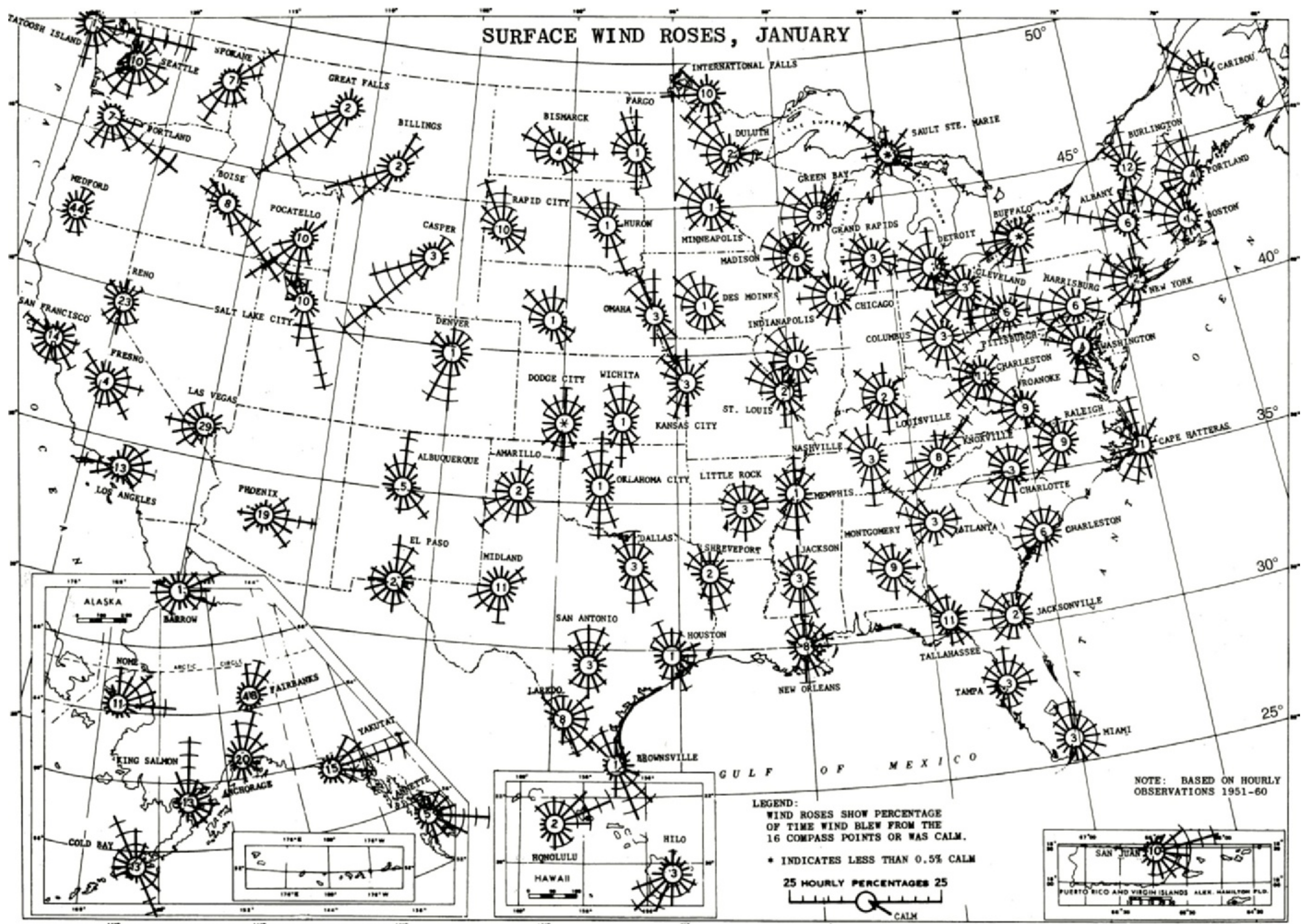


Figure 5.6d Surface wind roses, January. (From *Climate Atlas of the U.S.*, National Oceanic and Atmospheric Administration (NOAA), 1983.)

Fig. 5.6c. These values are critical in choosing the appropriate passive cooling techniques explained in Chapter 10.

H. Humidity: Even when the absolute moisture in the air remains fairly constant throughout the day, the RH will vary inversely with the temperature. Since hot air can hold more moisture than cold air, the RH will generally be lowest during the afternoons, and highest early in the morning, when temperatures are lowest.

The horizontal dashed lines define the comfort range for RH. However, even humidity levels within the comfort zone can be excessive if the coincident temperature is high enough. Thus, the building bioclimatic chart (D) is a better indicator of thermal comfort than either temperature or relative humidity by itself.

I. *Wind:* This chart shows the mean daily wind speeds in an open field at the reference city. The dashed line indicates the minimum wind speed required for effective natural ventilation in humid climates.

For wind direction, see the wind roses shown on maps of the United States in Figures 5.6d, 5.6e, 5.6f, and 5.6g. A wind rose shows the percentage of time the wind blows from the sixteen compass points or the air is calm. Each notch represents 5 percent of the time, and the number in the center circle represents the percentage of time there was no wind (calm). Maps of wind roses are included here for four critical months: the coldest (January), the hottest (July), and two transitional months (April and October).

The Web is an excellent source of climate information. Colorplate 37 is an example of a wind rose for Chicago downloaded from: www.wcc.nrcs.usda.gov/climate/windrose.html. These types of wind roses give not only the direction of the wind but also the wind speed and how often that occurs in percentage terms.

It is extremely important to note that local wind direction and speed can be very different from those at the weather station. All wind charts should, therefore, be used with great caution.

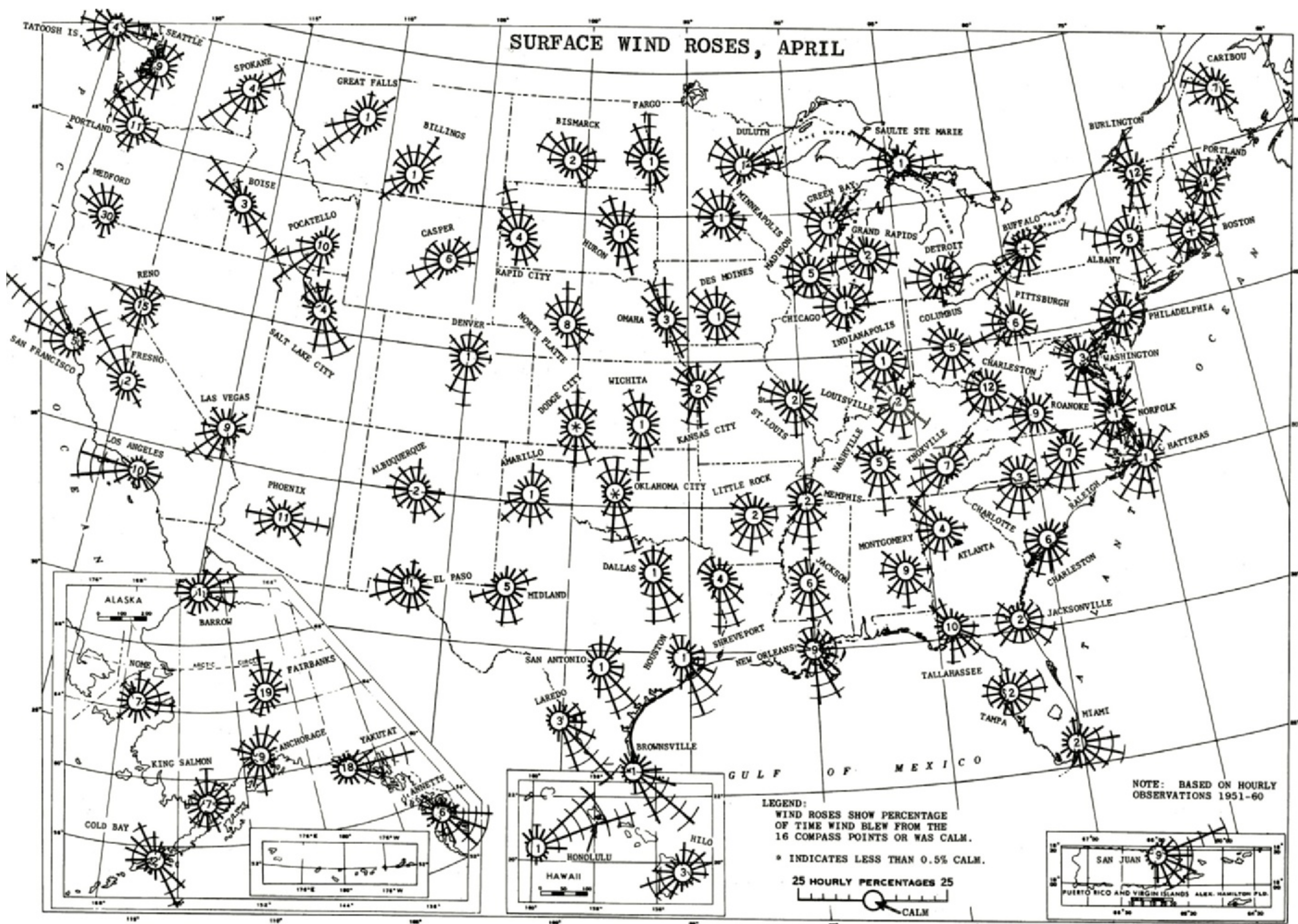


Figure 5.6e Surface wind roses, April. (From *Climate Atlas of the U.S.*, National Oceanic and Atmospheric Administration [NOAA], 1983.)

Table 5.6 Hours of Daylight Per Day*

Month	Latitude		
	30° N	40° N	50° N
January	10:25	9:39	8:33
February	11:09	10:43	10:07
March	11:58	11:55	11:51
April	12:53	13:15	13:45
May	13:39	14:23	15:24
June	14:04	15:00	16:21
July	13:54	14:45	15:57
August	13:14	13:46	14:30
September	12:22	12:28	12:39
October	11:28	12:28	12:39
November	10:39	9:59	9:04
December	10:14	9:21	8:06

*Values given are for the fifteenth day of each month.

J. *Sunshine:* This chart shows the percentage of the daylight hours of each month that the sun is shining. This data is useful for solar heating, shading, and daylighting design. The charts show that direct sunlight is plentiful in all climates. Since there are about 4460 hours of daylight in a year, the percentages in the charts indicate that there are more than 2000 hours of sunshine even in the cloudiest climate. Thus, direct sunshine is a major design consideration in all climates.

The number of daylight hours varies with both time of year and latitude. Table 5.6 contains values for 30°, 40°, and 50° north latitude for a typical day each month.

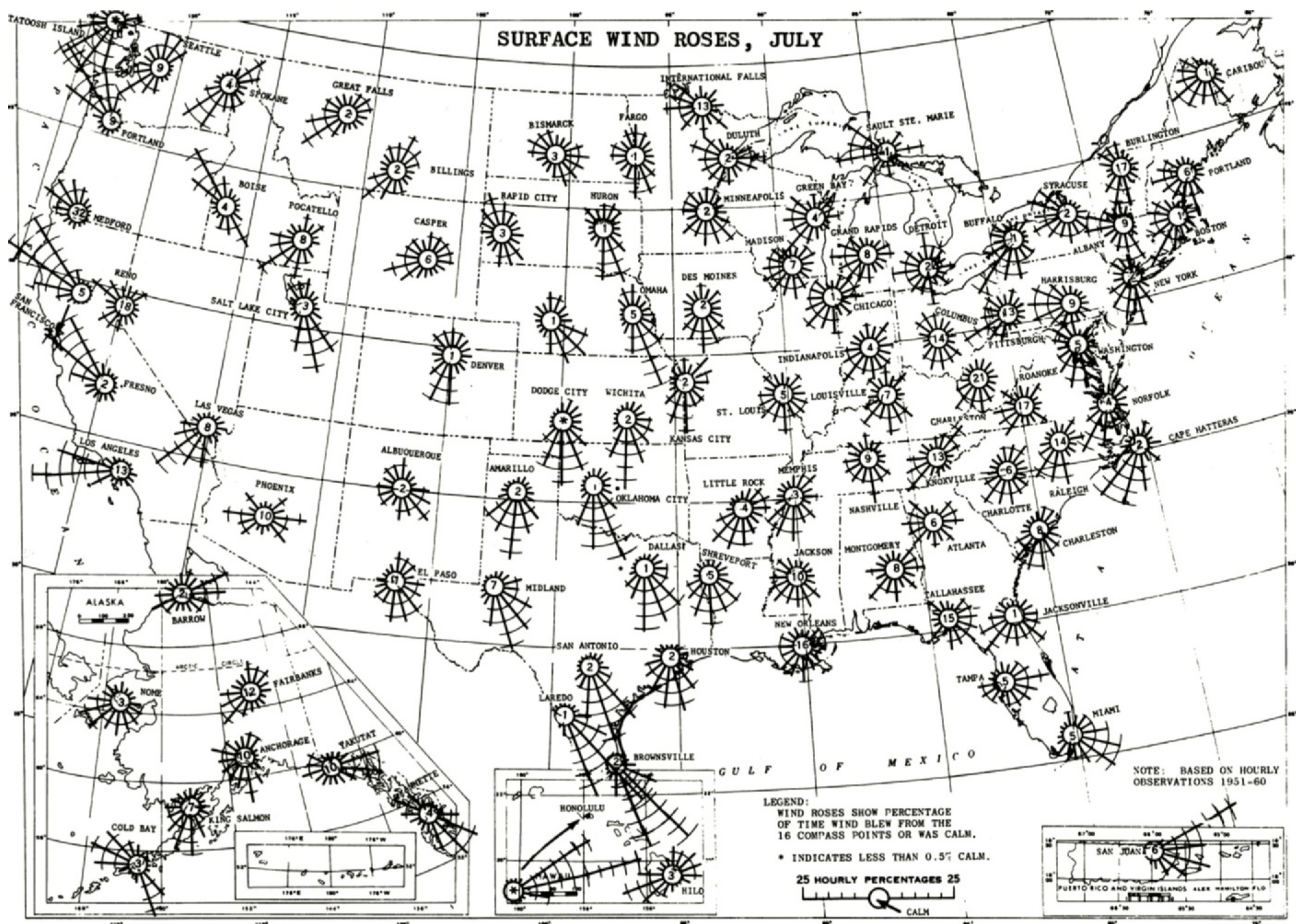


Figure 5.6f Surface wind roses, July (From *Climate Atlas of the U.S.*, National Oceanic and Atmospheric Administration [NOAA], 1983.)

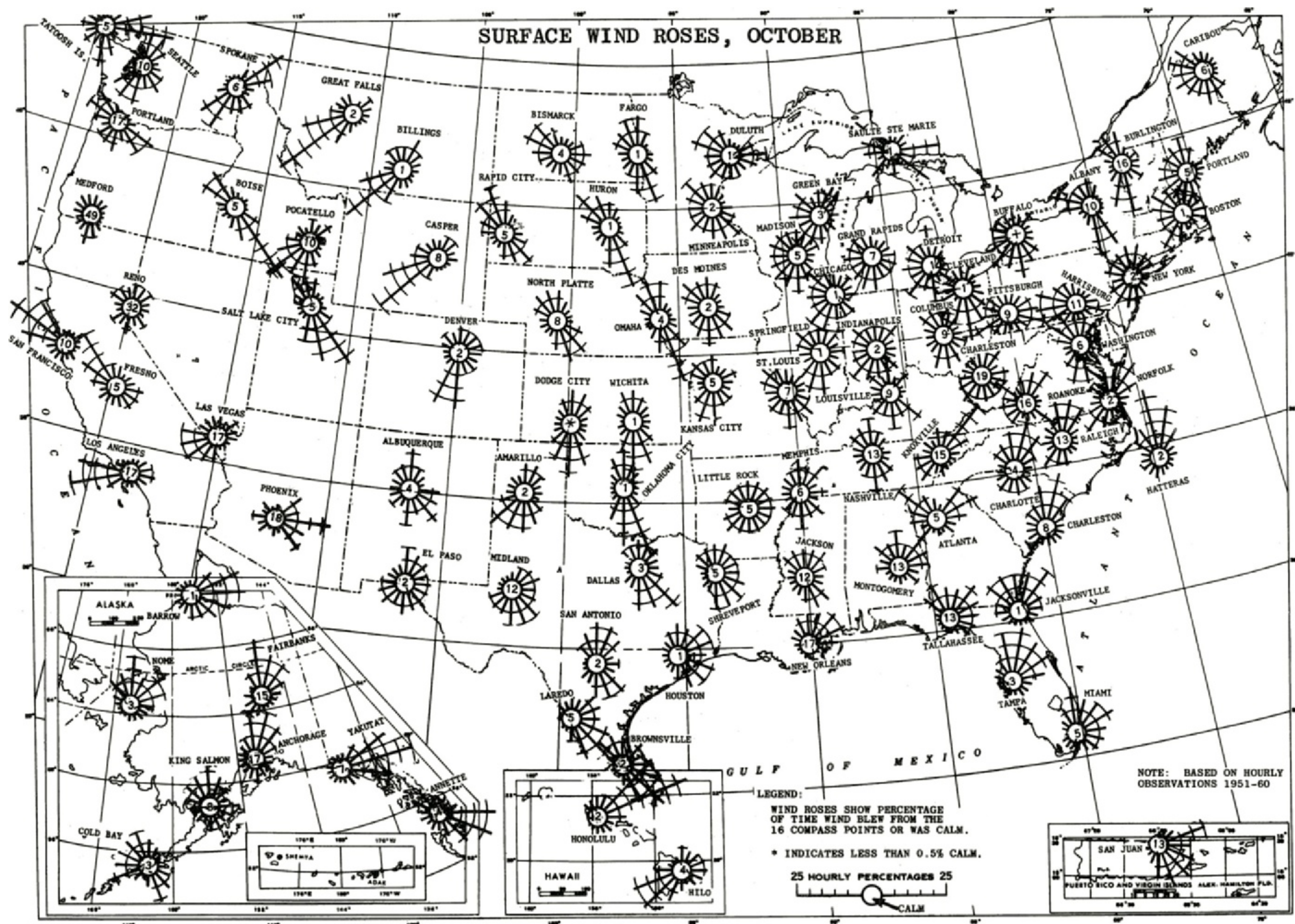


Figure 5.6g Surface wind roses, October. (From *Climate Atlas of the U.S.*, National Oceanic and Atmospheric Administration [NOAA], 1983.)

To determine the appropriate number of sunshine hours for a typical day of any month, multiply the number of daylight hours from Table 5.6 by the percentage of sunshine from the chart (J) for that month.

The annual percentage of sunshine is given at the right of the chart. Some solar-radiation data is also given enclosed in a rectangle. This data can give a quick estimate of the peak amount of solar heating or solar electricity that can be expected during one day in January on either a horizontal or vertical square foot.

K. *Degree-days:* Degree-days are a good indicator of total heating and cooling loads. Although the concept was developed to predict the amount of heating fuel required, it is now also used to predict the amount of cooling energy required. The degree-days shown here are for the typical base of 65°F (18°C). The difference between the average temperature of a particular day and 65°F (18°C) is the number of "degree-days" for that day. The chart shows the total number of degree-days for each month with heating degree-days above the zero line and cooling degree-days below. Thus, it is easy to determine visually both the length and depth of the heating and cooling periods and the relative size of each period. The yearly totals given in numerical form are also presented.

Degree-Day Rules of Thumb

Heating Degree-Days (HDDs)

1. Areas with more than 5500 HDDs per year are characterized by long, cold winters.
2. Areas with fewer than 2000 HDDs per year are characterized by very mild winters.

Cooling Degree-Days (CDDs)

1. Areas with more than 1500 CDDs per year are characterized by long, hot summers and substantial cooling requirements.
2. Areas with fewer than 500 CDDs per year are characterized by mild summers and little need for mechanical cooling.

5.7 RELATIVE HEATING AND COOLING LOADS

Although buildings must be designed for both heating and cooling loads in almost all parts of the United States, their design should reflect the relative importance of each. The map of the United States shown in Figure 5.7a is divided into five climate zones based only on heating and cooling degree-days. Figure 5.7b shows the relative heating and cooling energy used by residential buildings in Zones 1, 3, and 5. As one would expect, the heating load is greatest in the northernmost zone, but it may be surprising how large the heating load is also in the southernmost zone.

Figure 5.7c shows the relative heating, cooling, and ventilation energy used by commercial buildings in climate Zones 1, 3, and 5. Even though it is widely believed that commercial buildings need little heating, that is not true. In both Zones 1 and 3, heating is the dominant load, and even in Zone 5 heating is still an important load. The misconception probably arises from assuming that most commercial buildings are large internally dominated office buildings, which do actually have much larger cooling loads and smaller heating loads in all climates.

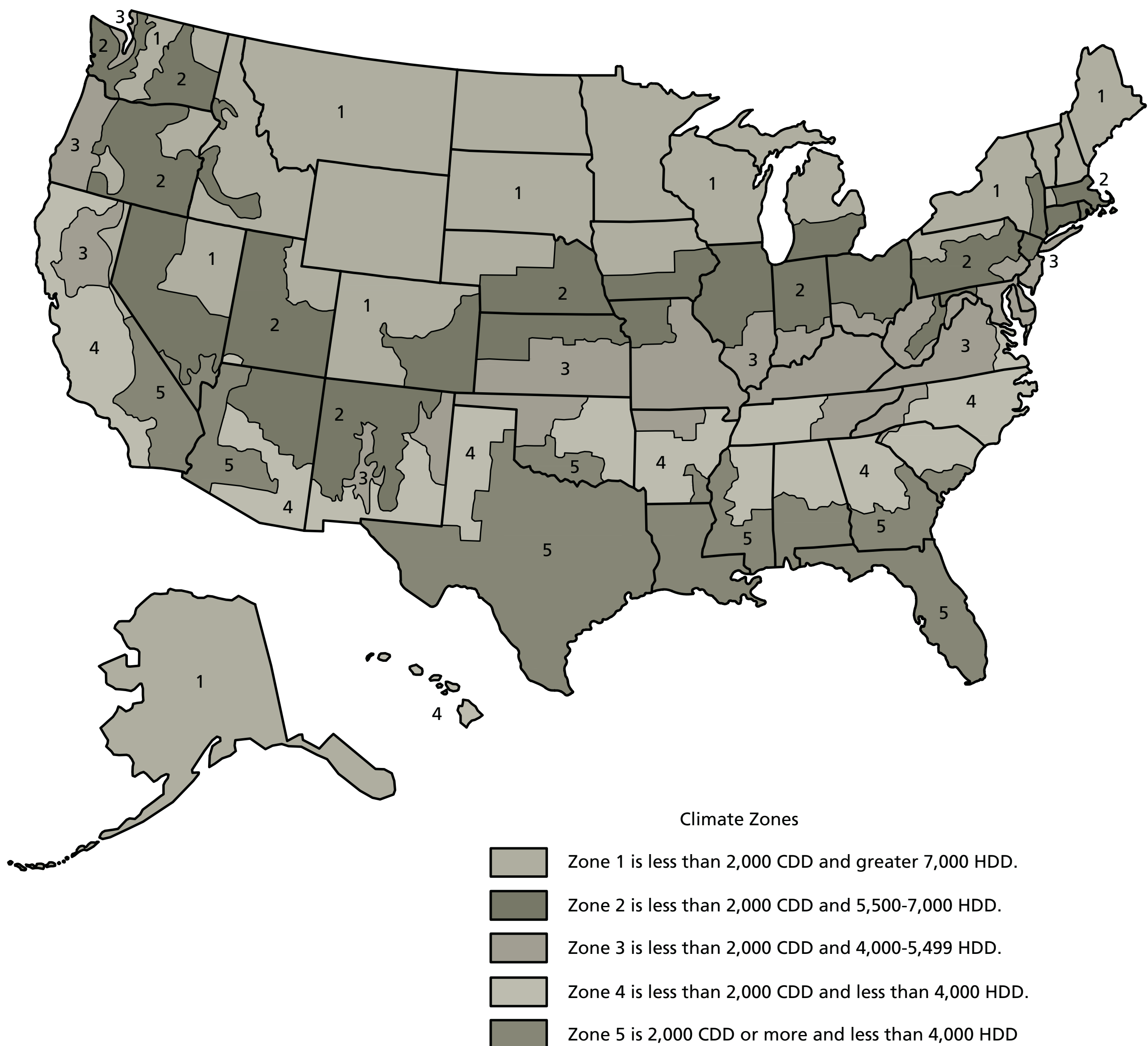


Figure 5.7a As the legend shows, this map divides the United States into only five climate zones, which are determined only by heating and cooling degree-days. (Source: The U.S. Energy Information Administration's study of the "Consumption and Efficiency" of buildings, 2003 and 2005.)

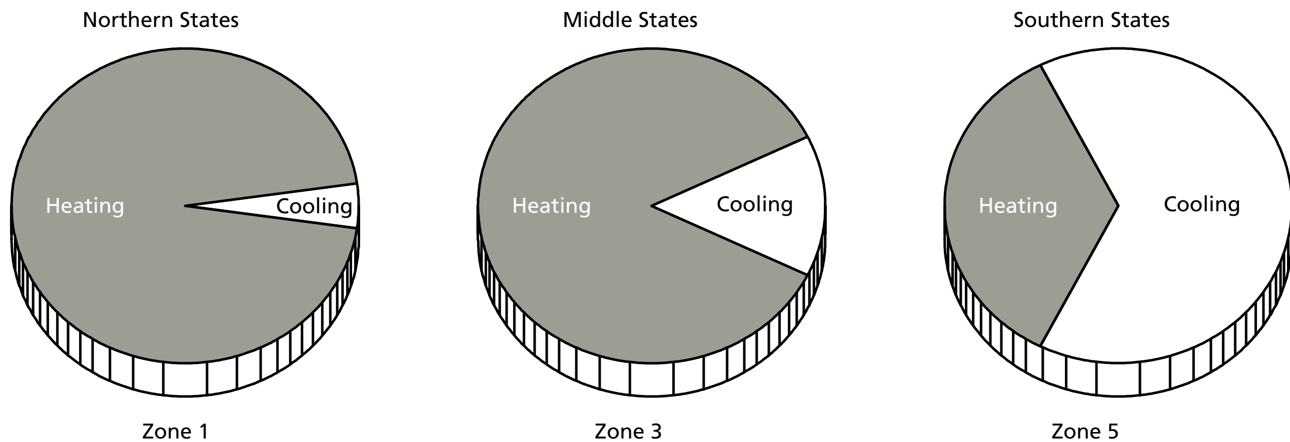


Figure 5.7b The relative heating and cooling energy consumption of residential buildings is shown for climate Zones 1, 3, and 5 as presented in Figure 5.7a. Not only is heating the major load in most of the country, it is important even the southernmost zone. Source: The U.S. Energy Information Administration's study of the "Consumption and Efficiency" of buildings, 2003 and 2005

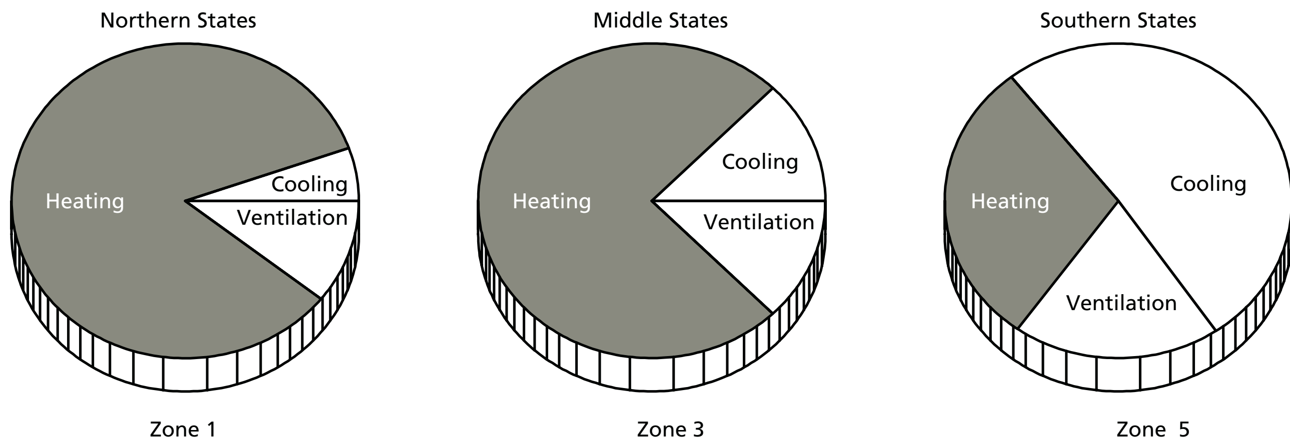


Figure 5.7c The relative heating, cooling, and ventilation energy consumption is shown for commercial buildings in climate Zones 1, 3, and 5 as described in Figure 5.7a. Not only is heating the major load in Zones 1 and 3, but it is important even in Zone 5. Keep in mind that most commercial buildings are not large office buildings, which have much larger cooling loads and smaller heating loads. Source: The U.S. Energy Information Administration's study of the "Consumption and Efficiency" of buildings, 2003 and 2005

5.8 ADDITIONAL CLIMATE INFORMATION

Additional excellent climate information is available on the Internet. For example, the average annual precipitation for the United States is shown in Colorplate 24. This and many other U.S. climate maps are available at www.wcc.nrcs.usda.gov/images/usprism.

Detailed climate information for each county in the United States is available by following these steps:

1. Go to www.wcc.nrcs.usda.gov/climate/prism.html.
2. Click on "Climate Reports."
3. Click on "Map Based Climate Information Retrieval."
4. Click on the state in which the county is located.
5. On the map of the state, click on the county for which the climate information is desired.

See the end of this chapter for more sources of climate information

5.9 CLIMATE INFORMATION FOR OTHER COUNTRIES

The seventeen Climatic Data Tables with their design guidelines can also be used to inform building design in other parts of the world. Because of its size and location on the planet, the United States has many of the climates that exist on earth.

To use the seventeen U.S. climate regions presented in this chapter when SI units are desired, use the following conversion factors:

1. Temperature—use the conversion factors in Appendix L to change °F to °C.
2. Wind speed—multiply mph by 1.6 to get kph or multiply mph by 0.447 to get m/s.
3. Peak daily solar radiation—multiply Btu/day $\times$ ft^2 by 7.29 to get Wh/day $\times$ m^2.
4. Degree-days—
   Multiply HDD (°F) by 0.56 to HDD (°C)
   Multiply CDD (°F) by 0.56 to get CDD (°C)

CLIMATE REGION 1

REFERENCE CITY: HARTFORD, CONNECTICUT



The Climate

This region, which includes New England, has a severe climate of mostly cool and cold temperatures that often drop far below freezing in the winter. Snow is common in most of the region. Winter winds, which greatly add to winter discomfort, are usually from northwesterly and westerly directions. Since sunshine is available in more than 50 percent of the daylight hours, solar heating has potential even here. Reflections off the snow can significantly increase winter sun on south facades.

Summers are mostly mild, with short hot periods. The extreme annual temperature range can reach more than 120°F, which makes this one of the most rugged regions in the United States. There are short periods in the summer when the humidity in combination with the temperature is too high. During the summer, the sun can be a liability; thus, shading is required. Summer winds are generally southerly and are an asset in achieving comfort.

The annual precipitation is about 44 in. (110 cm) and occurs fairly uniformly throughout the year.



*Climatic Design Priorities**

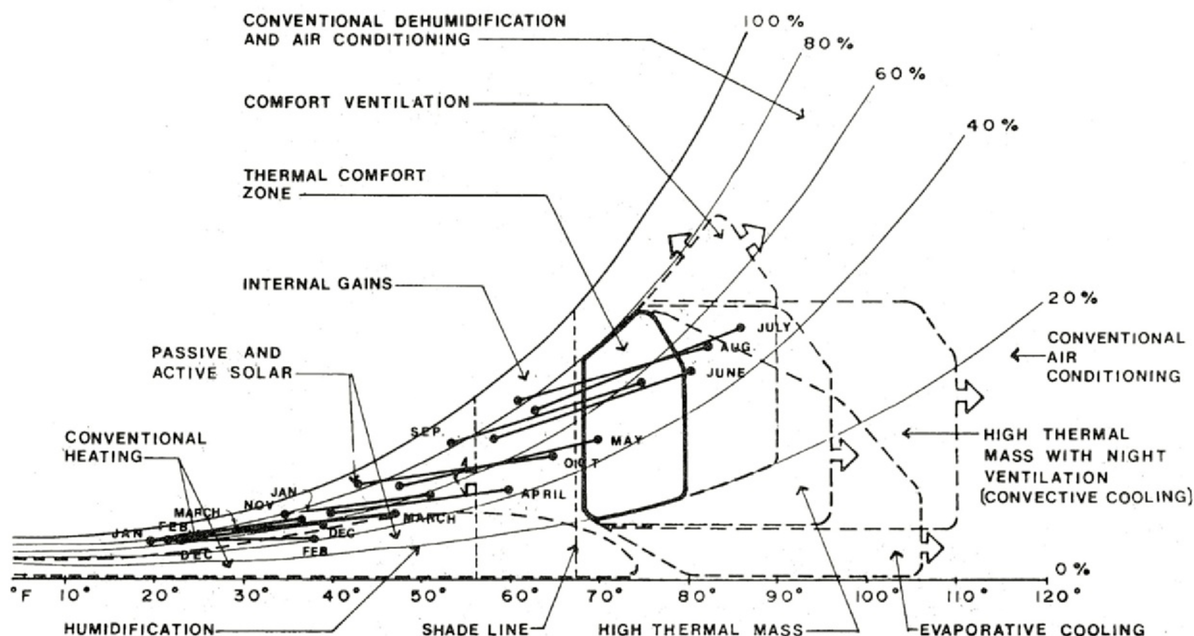
1st Keep heat in and cold temperatures out during the winter. (I)
2nd Protect from the cold winter winds. (II)
3rd Let the winter sun in. (III)

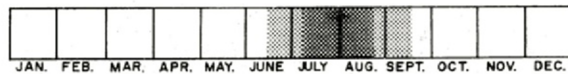
Lower priority

4th Protect from the summer sun. (IV)
5th Use natural ventilation for summer cooling. (V)

*These climatic design priorities are for envelope-dominated building types only. See Section 5.10 for a list of design strategies appropriate for achieving each of these priorities. Use the Roman numerals to find the relevant lists.

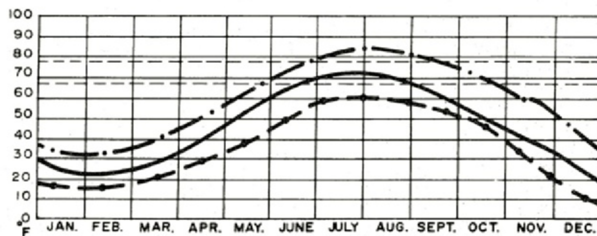
Note: For an explanation of this and the following Climatic Data Tables, see Section 5.6.





BASIC CLIMATIC CONDITION

		% of year
	Comfortable period	12
	too hot	13
	too cold	75



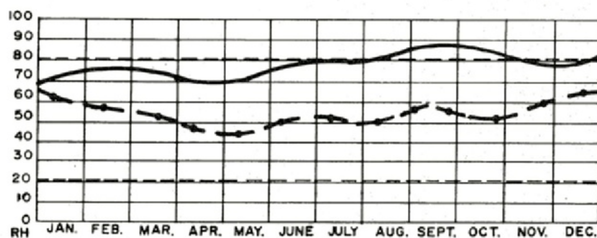
TEMPERATURE

range of comfortable temp.

afternoon maximum temperature

average daily temperature

morning minimum temperature

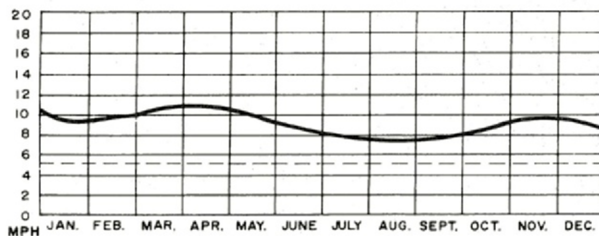


RELATIVE HUMIDITY

average morning humidity

average afternoon humidity

range of comfortable humidity

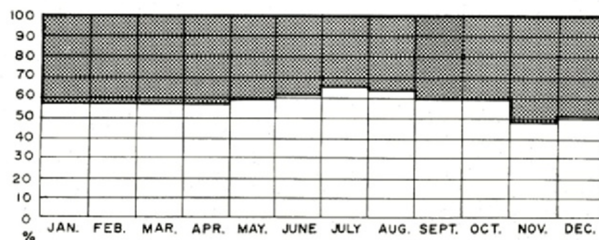


WIND SPEED

mean daily wind speed

wind speed for effective natural ventilation

for wind direction see the wind roses on pages 42–45.

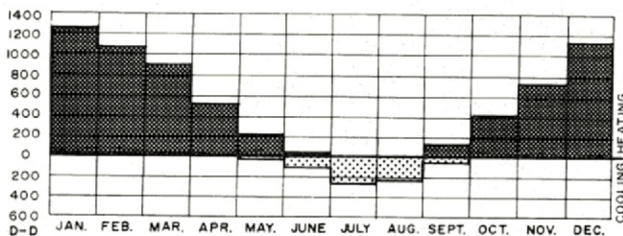


SUNSHINE

average % of daylight hours

annual sunshine = 57 %

peak solar radiation in January
horiz. sq. ft. = 500 btu/day
vert. sq. ft. = 900 btu/day



DEGREE-DAYS

		annual
	heating degree-days	6,174
	cooling degree-days	666

CLIMATE REGION 2

REFERENCE CITY: MADISON, WISCONSIN



The Climate

The climate of the northern plains is similar to that of region I but is even more severe because this inland region is far from the moderating effect of the oceans. The main concern is with the winter low temperatures, which are often combined with fairly high wind speeds.

Although summers are very hot, they are less of a concern because they are short. The sun is an asset in the winter and a liability in the summer.

The annual precipitation of about 31 in. (78 cm) occurs throughout the year, but summer months receive over twice as much as winter months.



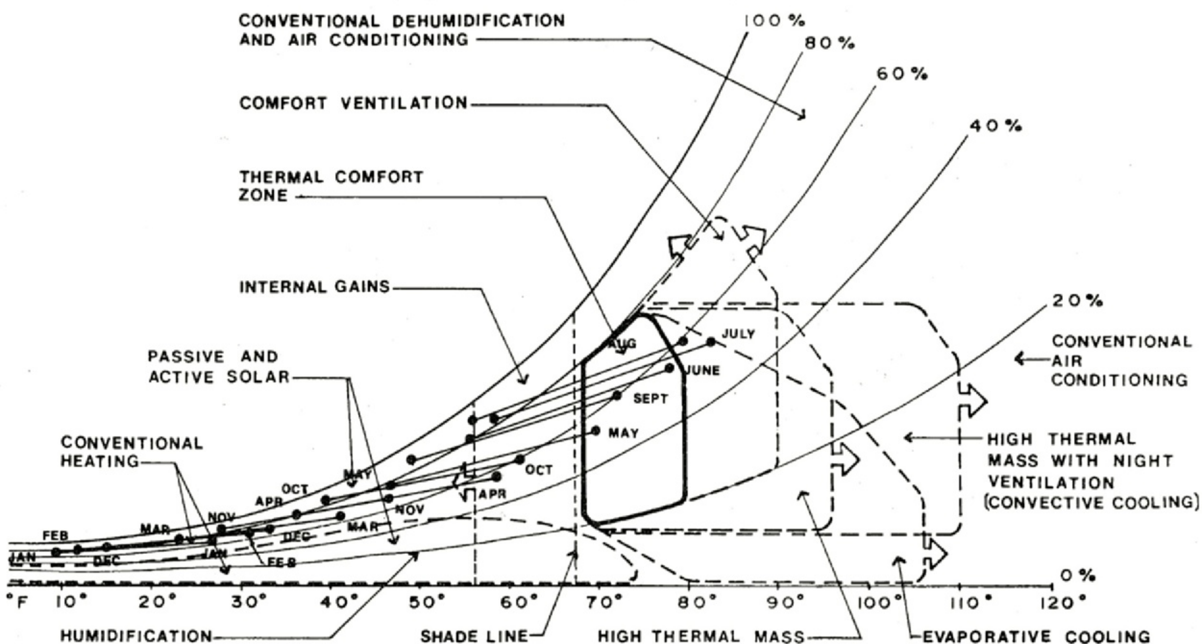
*Climatic Design Priorities**

1st Keep heat in and cold temperatures out in the winter. (I)
2nd Protect from the cold winter winds. (II)
3rd Let the winter sun in. (III)

Lower priority

4th Use thermal mass to reduce day-to-night temperature swings in the summer. (VII)
5th Protect from the summer sun. (IV)
6th Use natural ventilation for summer cooling. (V)

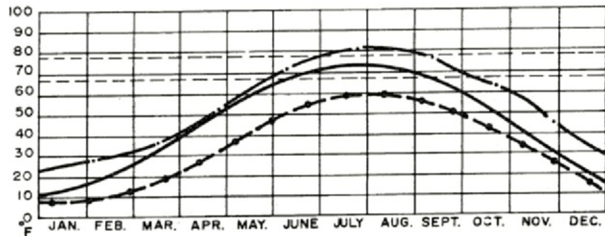
*These climatic design priorities are for envelope-dominated building types only. See Section 5.10 for a list of design strategies appropriate for achieving each of these priorities. Use the Roman numerals to find the relevant lists.





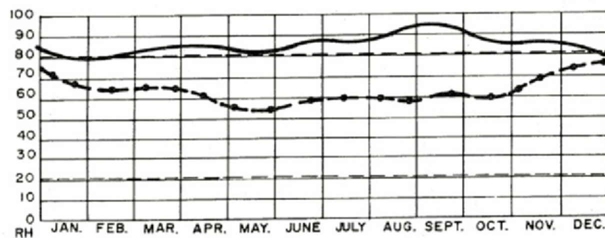
BASIC CLIMATIC CONDITION

		% of year
	Comfortable period	12
	too hot	12
	too cold	76



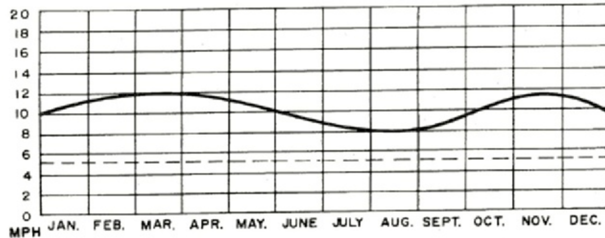
TEMPERATURE

range of comfortable temp.
afternoon maximum temperature
average daily temperature
morning minimum temperature



RELATIVE HUMIDITY

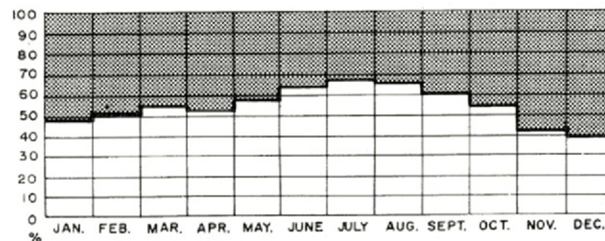
average morning humidity
average afternoon humidity
range of comfortable humidity



WIND SPEED

mean daily wind speed
wind speed for effective natural ventilation

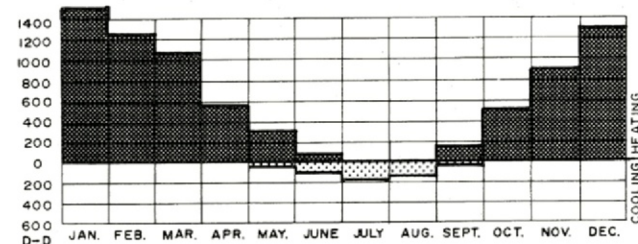
for wind direction see the wind roses on pages 42–45.



SUNSHINE
average % of daylight hours

annual sunshine = 54 %

peak solar radiation in January
horiz. sq. ft. = 600 btu/day
vert. sq. ft. = 1100 btu/day



DEGREE-DAYS

		annual
	heating degree-days	7,642
	cooling degree-days	467

CLIMATE REGION 3

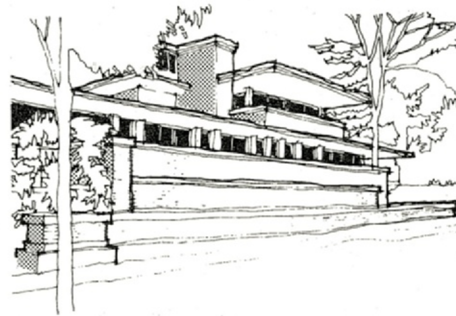
REFERENCE CITY: INDIANAPOLIS, INDIANA

The Climate

This climate of the Midwest is similar to that of regions 1 and 2, but it is somewhat milder in winter. Cold winds, however, are still an important concern. The mean annual snowfall ranges from 12 to 60 in. (30 to 150 cm). There is some potential for solar energy in the winter since the sun shines more than 40 percent of the daylight hours.

Significant cooling loads are common since high summer temperatures often coincide with high humidity. Winds are an asset during the summer.

The annual precipitation is about 39 in. (98 cm) and occurs fairly uniformly throughout the year.





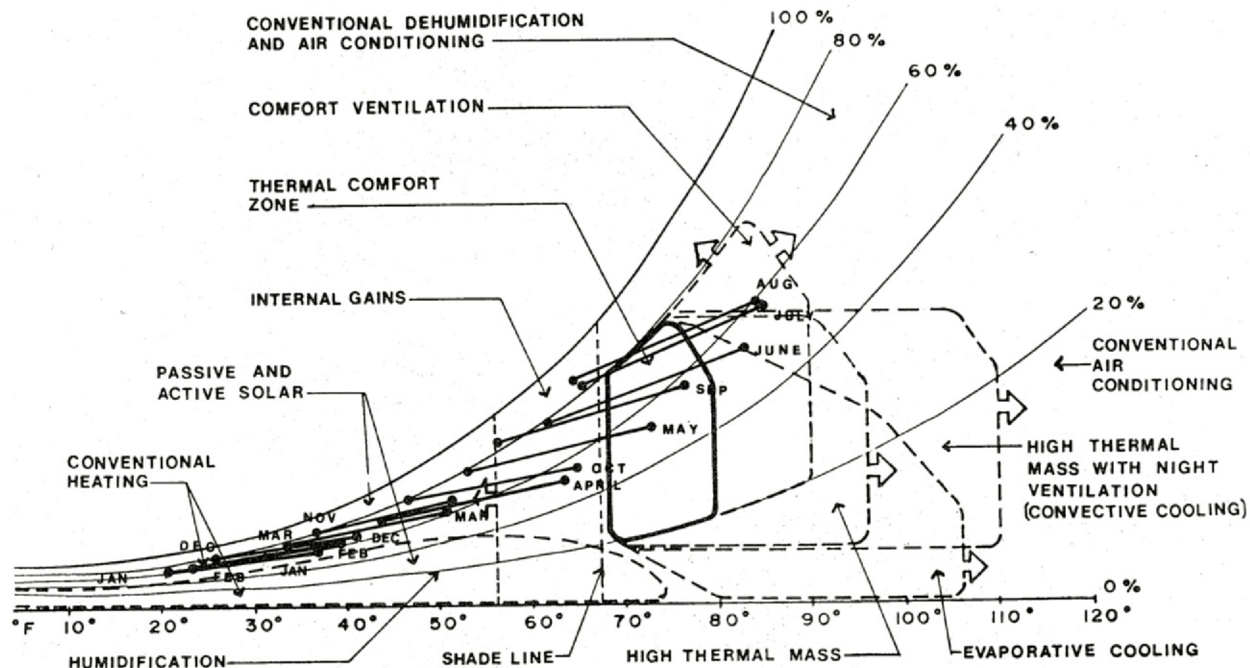
*Climatic Design Priorities**

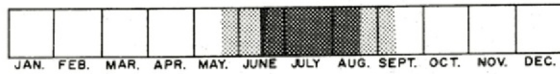
1st Keep heat in and cold temperatures out in the winter. (I)
2nd Protect from the cold winter winds. (II)
3rd Let the winter sun in. (III)

Lower priority

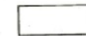
4th Keep hot temperatures out during the summer. (VIII)
5th Protect from the summer sun. (IV)
6th Use natural ventilation for summer cooling. (V)

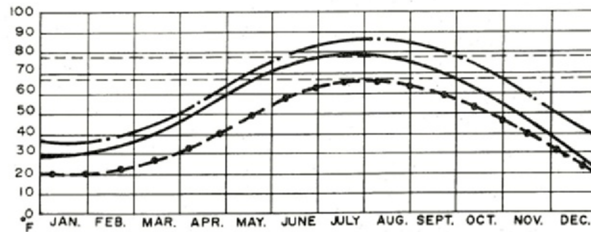
*These climatic design priorities are for envelope-dominated building types only. See Section 5.10 for a list of design strategies appropriate for achieving each of these priorities. Use the Roman numerals to find the relevant lists.





BASIC CLIMATIC CONDITION

		% of year
	Comfortable period	14
	too hot	20
	too cold	66



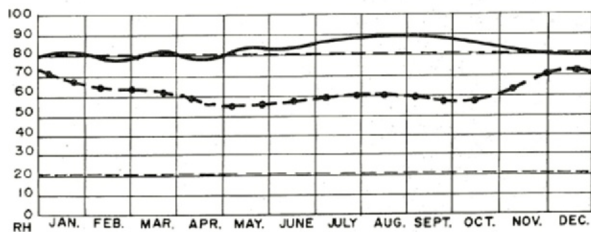
TEMPERATURE

 range of comfortable temp.

 afternoon maximum temperature

 average daily temperature

 morning minimum temperature

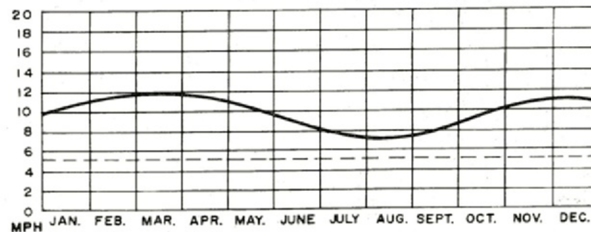


RELATIVE HUMIDITY

 average morning humidity

 average afternoon humidity

 range of comfortable humidity

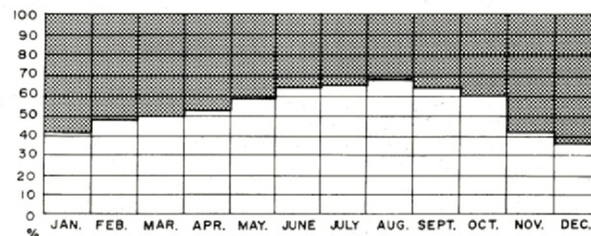


WIND SPEED

 mean daily wind speed

 wind speed for effective natural ventilation

for wind direction see the wind roses on pages 42–45.

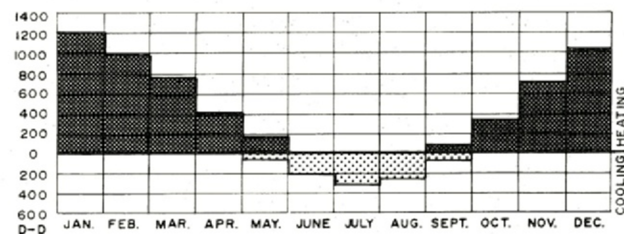


SUNSHINE

average % of daylight hours

annual sunshine = 55 %

peak solar radiation in January
horiz. sq. ft. = 500 btu/day
vert. sq. ft. = 800 btu/day



DEGREE-DAYS

		annual
	heating degree-days	5,650
	cooling degree-days	988

CLIMATE REGION 4

REFERENCE CITY: SALT LAKE CITY, UTAH



The Climate

This is the climate of the Great Plains, intermountain basin, and plateaus. It is a semiarid climate with cold, windy winters and warm, dry summers. Winters are very cold, with frequent but short storms alternating with sunny periods.

Summer temperatures are high, but the humidity is low. Thus, the diurnal temperature range is high and summer nights are generally cool. There is much potential for both passive heating and cooling.

The annual precipitation is about 15 in. (38 cm) and occurs fairly uniformly throughout the year, but spring is the wettest season.



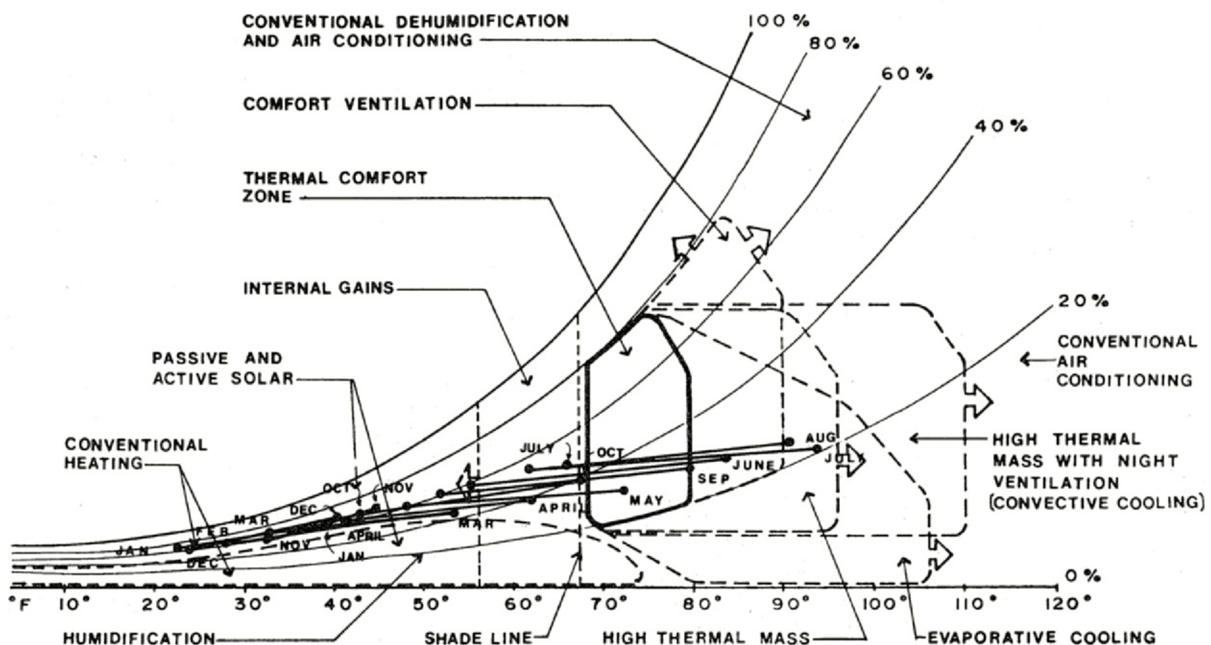
*Climatic Design Priorities**

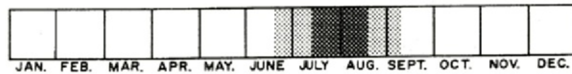
1st Keep the heat in and the cold temperatures out during the winter. (I)
2nd Let the winter sun in. (III)
3rd Protect from the cold winter winds. (II)

Lower priority

4th Use thermal mass to reduce day-to-night temperature swings in the summer. (VII)
5th Protect from the summer sun. (IV)
6th Use evaporative cooling in the summer. (IX)
7th Use natural ventilation for summer cooling. (V)

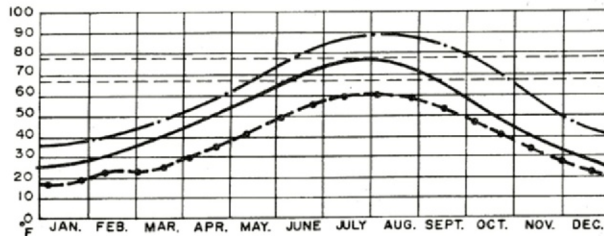
*These climatic design priorities are for envelope-dominated building types only. See Section 5.10 for a list of design strategies appropriate for achieving each of these priorities. Use the Roman numerals to find the relevant lists.





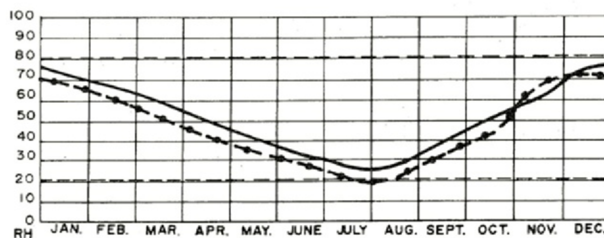
BASIC CLIMATIC CONDITION

		% of year
	Comfortable period	12
	too hot	11
	too cold	77



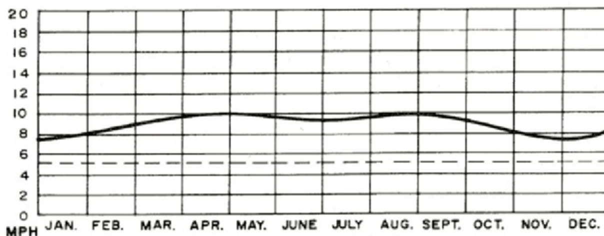
TEMPERATURE

range of comfortable temp.
afternoon maximum temperature
average daily temperature
morning minimum temperature



RELATIVE HUMIDITY

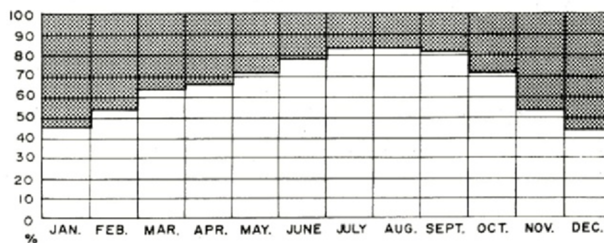
average morning humidity
average afternoon humidity
range of comfortable humidity



WIND SPEED

mean daily wind speed
wind speed for effective natural ventilation

for wind direction see the wind roses on pages 42–45.

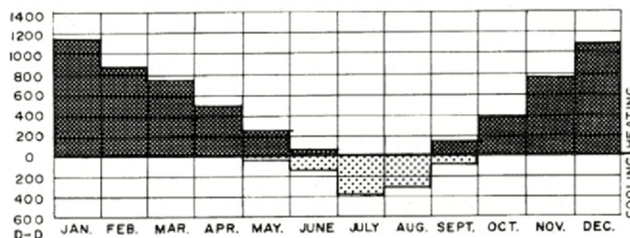


SUNSHINE

average % of daylight hours

annual sunshine = 66 %

peak solar radiation in January
horiz. sq. ft. = 700 btu/day
vert. sq. ft. = 1100 btu/day

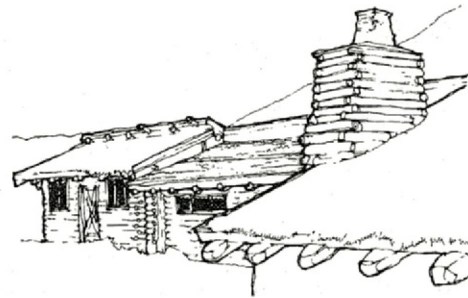


DEGREE-DAYS

		annual
	heating degree-days	5802
	cooling degree-days	981

CLIMATE REGION 5

REFERENCE CITY: ELY, NEVADA



The Climate

This is a high, mountainous, and semiarid region above 7000 ft (2100 m) in southern latitudes and above 6000 ft (1800 m) in northern latitudes. It is a mostly cool and cold climate. Snow is plentiful and may remain on the ground for more than half the year. The temperature and, thus, the snow cover vary tremendously with the slope orientation and elevation. Heating is required most of the year. Fortunately, sunshine is available more than 60 percent of the winter daylight hours.

Summer temperatures are modest, and comfort is easily achieved by natural ventilation. Summer nights are quite cool because of the high diurnal temperature range.

The annual precipitation is about 9 in. (23 cm) and occurs fairly uniformly throughout the year.



*Climatic Design Priorities**

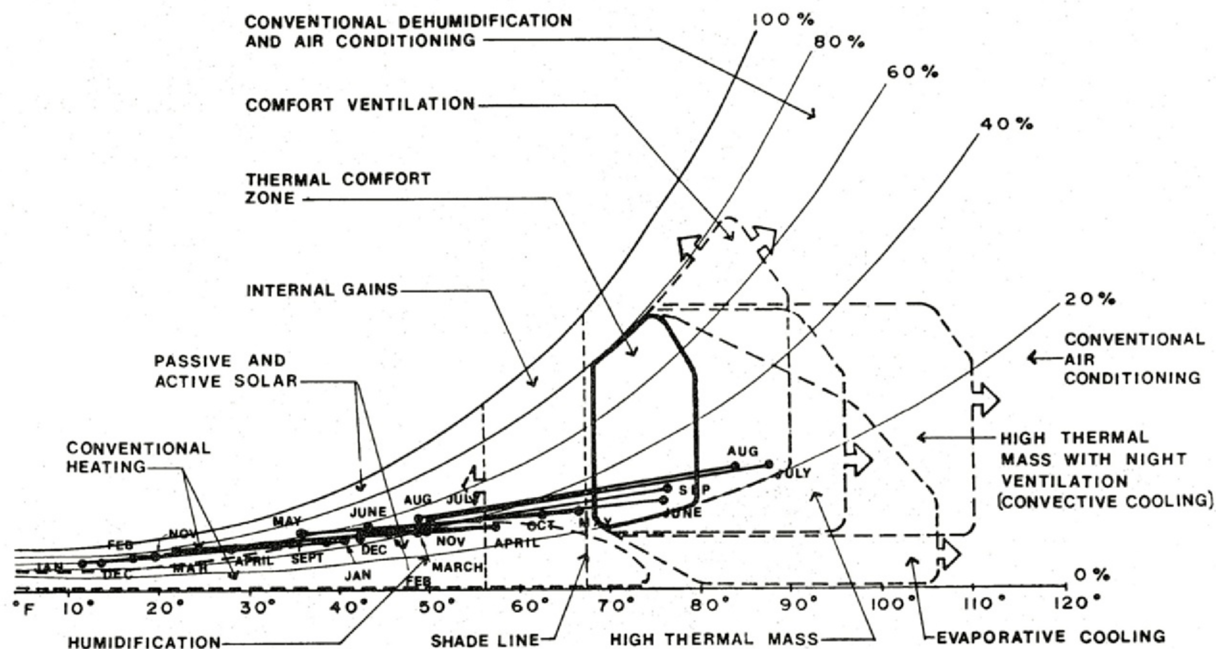
1st Keep the heat in and the cold air out during the winter. (I)

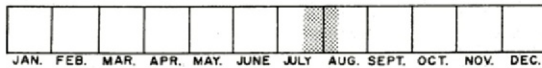
2nd Let the winter sun in. (III)

3rd Protect from the cold winter winds. (II)

4th Use thermal mass to reduce day-to-night temperature swings in the summer. (VII)

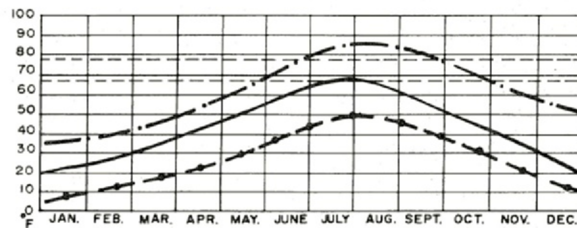
*These climatic design priorities are for envelope-dominated building types only. See Section 5.10 for a list of design strategies appropriate for achieving each of these priorities. Use the Roman numerals to find the relevant lists.





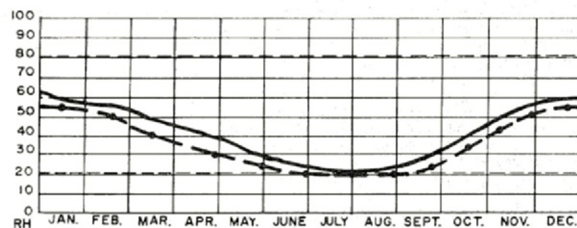
BASIC CLIMATIC CONDITION

	% of year
Comfortable period	8
too hot	0
too cold	92



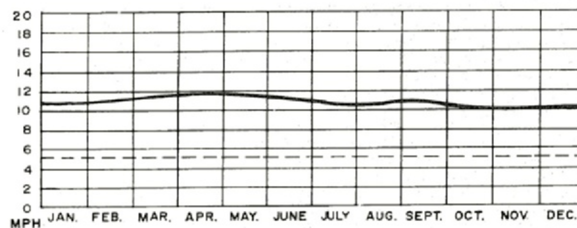
TEMPERATURE

- range of comfortable temp.
- afternoon maximum temperature
- average daily temperature
- morning minimum temperature



RELATIVE HUMIDITY

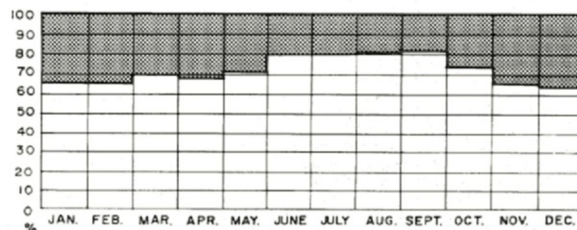
- average morning humidity
- average afternoon humidity
- range of comfortable humidity



WIND SPEED

- mean daily wind speed
- wind speed for effective natural ventilation

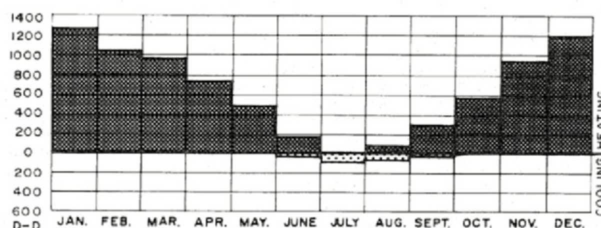
for wind direction see the wind roses on pages **42–45**.



SUNSHINE
average % of daylight hours

annual sunshine = 73 %

peak solar radiation in January
horiz. sq. ft. = 900 btu/day
vert. sq. ft. = 1600 btu/day



DEGREE-DAYS

	annual
heating degree-days	7,700
cooling degree-days	192

CLIMATE REGION 6

REFERENCE CITY: MEDFORD, OREGON





The Climate

The northern California, Oregon, and Washington coastal region has a very mild climate. In winter the temperatures are cool and rain is common. Although the skies are frequently overcast, solar heating is still possible because of the small heating load created by the mild climate. The high RH is not a significant problem because it does not coincide with high summer temperatures.

The region has a large variation in microclimates because of changes in both elevation and distance from the coast. In some areas the winter winds are a significant problem. A designer should, therefore, obtain additional local weather data.

The annual precipitation is about 20 in. (50 cm) but most of it occurs in the winter months. The summers are quite dry and sunny.

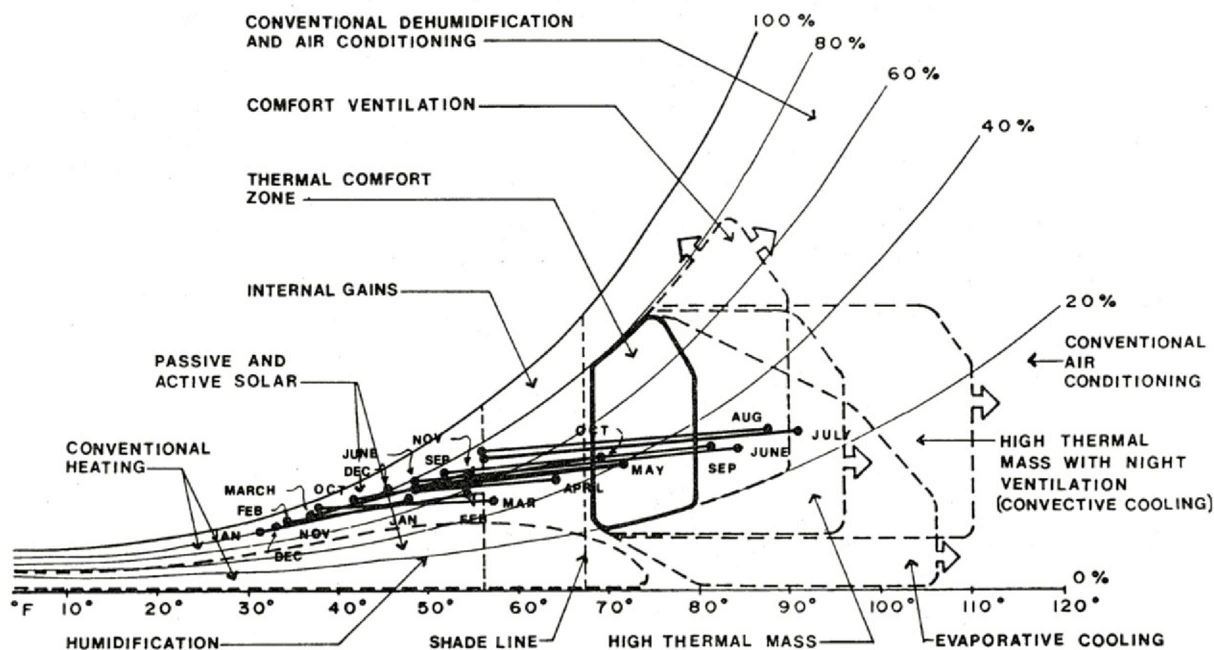
*Climatic Design Priorities**

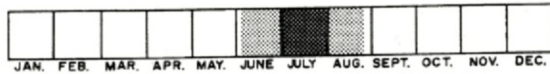
1st Keep the heat in and the cold temperatures out during the winter. (I)

2nd Let the winter sun in (mostly diffused sun because of the clouds). (III)

3rd Protect from the cold winter winds. (II)

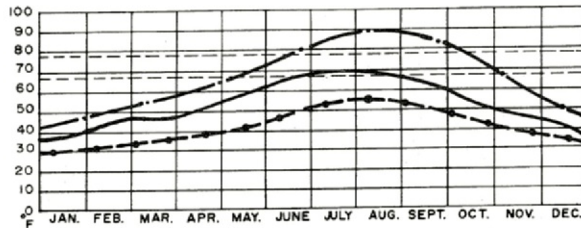
*These climatic design priorities are for envelope-dominated building types only. See Section 5.10 for a list of design strategies appropriate for achieving each of these priorities. Use the Roman numerals to find the relevant lists.





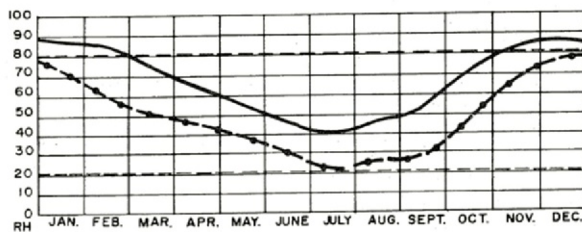
BASIC CLIMATIC CONDITION

	% of year
Comfortable period	13
too hot	8
too cold	79



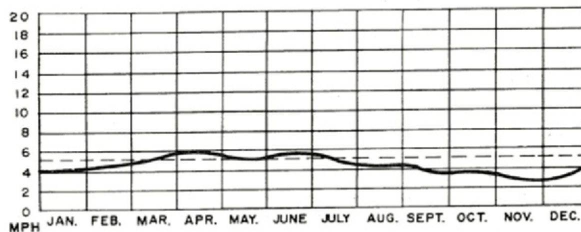
TEMPERATURE

range of comfortable temp.
afternoon maximum temperature
average daily temperature
morning minimum temperature



RELATIVE HUMIDITY

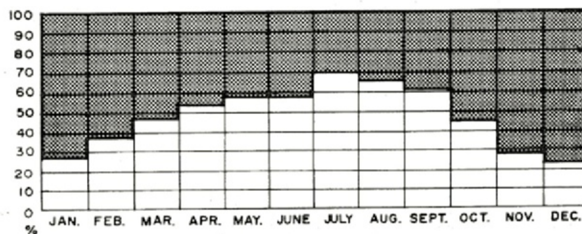
average morning humidity
average afternoon humidity
range of comfortable humidity



WIND SPEED

mean daily wind speed
wind speed for effective natural ventilation

for wind direction see the wind roses on pages 42–45.

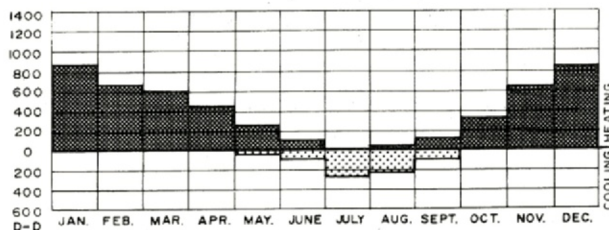


SUNSHINE

average % of daylight hours

annual sunshine = 47 %

peak solar radiation in January
horiz. sq. ft. = 300 btu/day
vert. sq. ft. = 550 btu/day

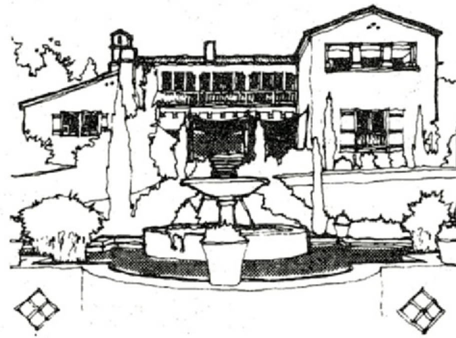


DEGREE-DAYS

	annual
heating degree-days	4798
cooling degree-days	645

CLIMATE REGION 7

REFERENCE CITY: FRESNO, CALIFORNIA



The Climate

This region includes California's Central Valley and parts of the central coast. Winters are moderately cold, with most of the annual rain of about 11 in. (28 cm) falling during that period. Winter sunshine, nevertheless, is plentiful.

Summers are hot and dry. The low humidity causes a large diurnal temperature range; consequently, summer nights are cool. Rain is rare during the summer months.

Since spring and fall are very comfortable, and much of the rest of the year is not very uncomfortable, outdoor living is very popular in this region.

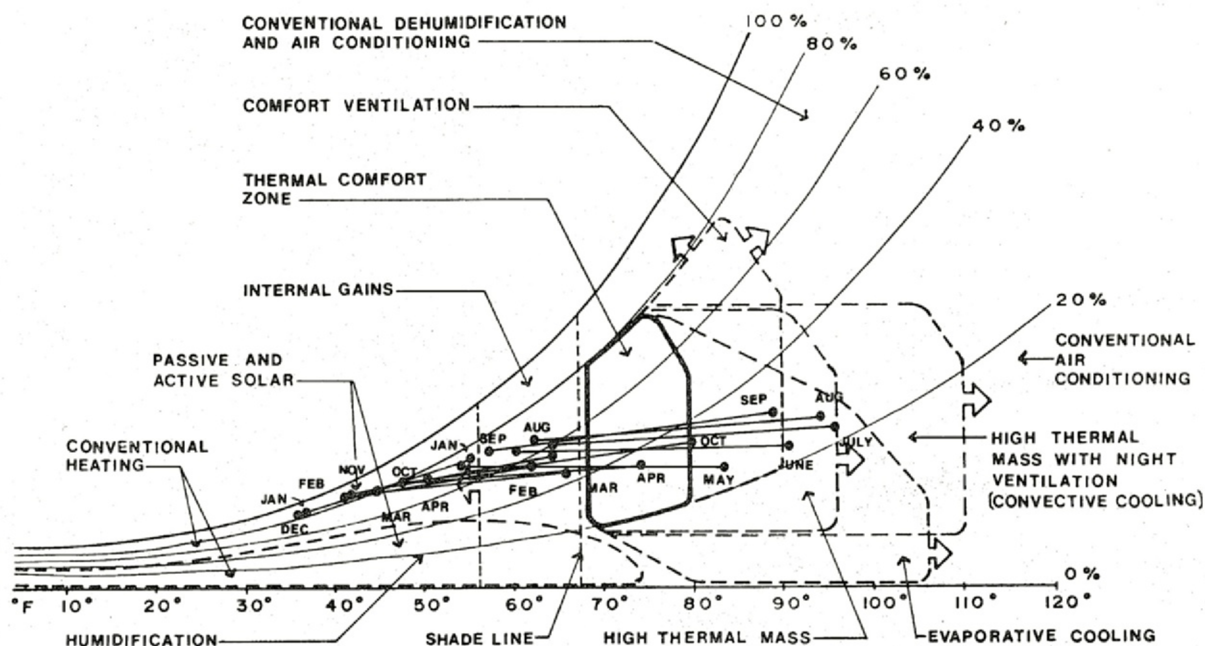
Because of the varying distances to the ocean, significant changes in microclimate exist. Near the coast the temperatures are more moderate in both winter and summer. Neither winter nor summer dominates the climate of this region.

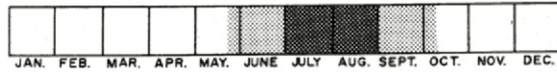


*Climatic Design Priorities**

1st Keep the heat in and cold temperatures out during the winter. (I)
2nd Keep hot temperatures out during the summer. (VIII)
3rd Let the winter sun in. (III)
4th Protect from the summer sun. (IV)
5th Use thermal mass to reduce day-to-night temperature swings during the summer. (VII)
6th Use natural ventilation for cooling in the spring and fall. (V)
7th Use evaporative cooling in the summer. (IX)
8th Protect from the cold winter winds. (II)

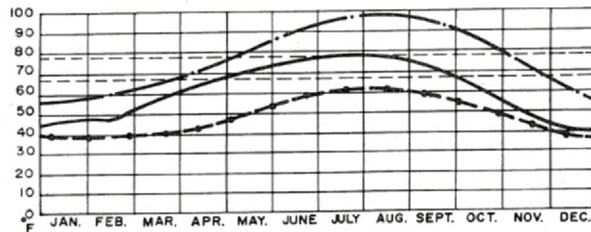
*These climatic design priorities are for envelope-dominated building types only. See Section 5.10 for a list of design strategies appropriate for achieving each of these priorities. Use the Roman numerals to find the relevant lists.





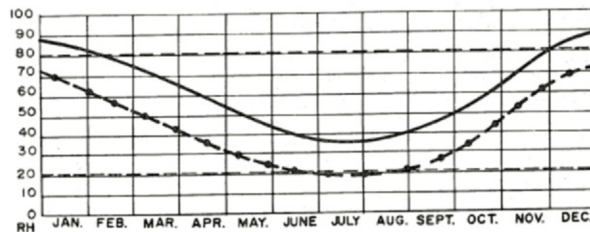
BASIC CLIMATIC CONDITION

	% of year
Comfortable period	21
too hot	17
too cold	62



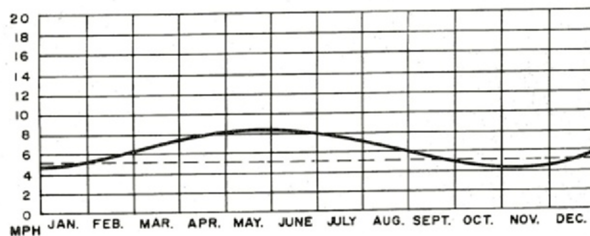
TEMPERATURE

range of comfortable temp.
afternoon maximum temperature
average daily temperature
morning minimum temperature



RELATIVE HUMIDITY

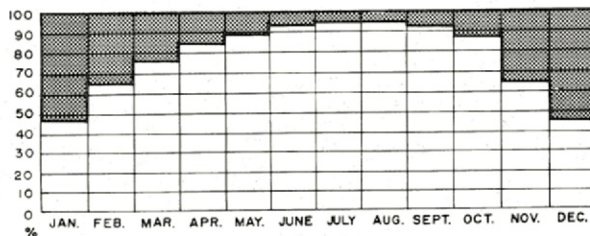
average morning humidity
average afternoon humidity
range of comfortable humidity



WIND SPEED

mean daily wind speed
wind speed for effective natural ventilation

for wind direction see the wind roses on pages 42–45.

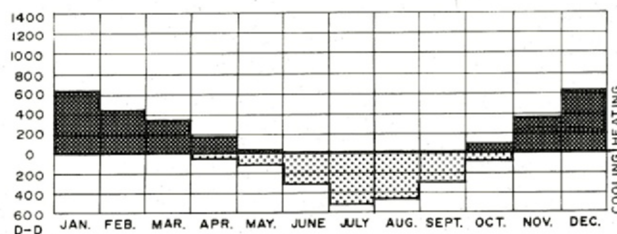


SUNSHINE

average % of daylight hours

annual sunshine = 78 %

peak solar radiation in January
horiz. sq. ft. = 600 btu/day
vert. sq. ft. = 1050 btu/day



DEGREE-DAYS

	annual
heating degree-days	2,647
cooling degree-days	1,769

CLIMATE REGION 8

REFERENCE CITY: CHARLESTON, SOUTH CAROLINA



The Climate

This mid-Atlantic-coast climate is relatively temperate, with four distinct seasons. Although summers are very hot and humid and winters are somewhat cold, spring and fall are generally quite pleasant. Summer winds are an important asset in this hot and humid climate.

The annual precipitation is about 47 in. (118 cm) and occurs fairly uniformly throughout the year. Summer, however, is the wettest season, with thunderstorms common during that period. Tropical storms are an occasional possibility.



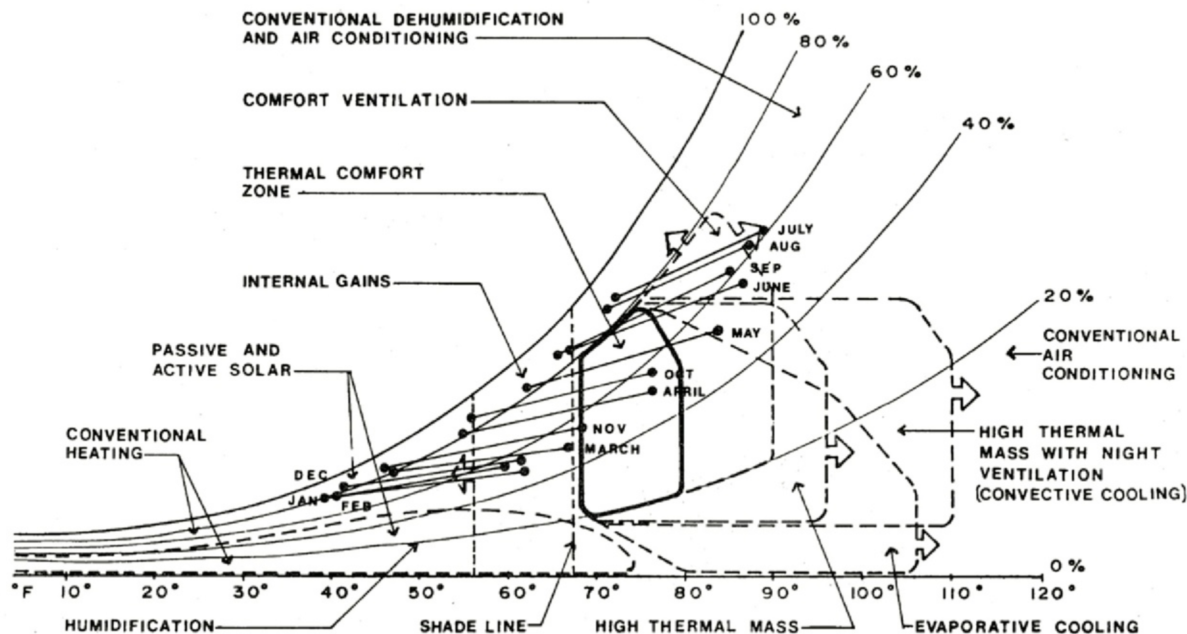
*Climatic Design Priorities**

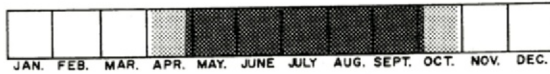
1st Keep the heat in and the cold temperatures out during the winter. (I)
2nd Use natural ventilation for summer cooling. (V)
3rd Let the winter sun in. (III)
4th Protect from the summer sun. (IV)

Lower priority

5th Protect from the cold winter winds. (II)
6th Avoid creating additional humidity during the summer. (X)

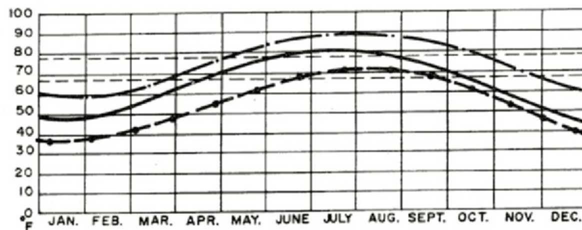
*These climatic design priorities are for envelope-dominated building types only. See Section 5.10 for a list of design strategies appropriate for achieving each of these priorities. Use the Roman numerals to find the relevant lists.





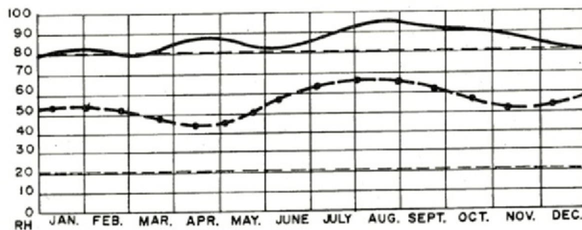
BASIC CLIMATIC CONDITION

	% of year
Comfortable period	12
too hot	42
too cold	46



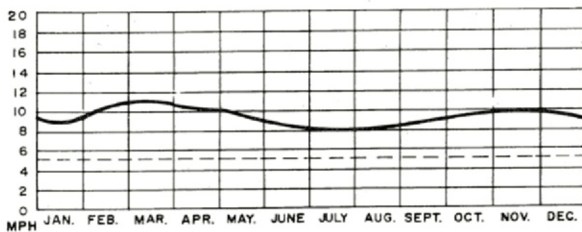
TEMPERATURE

range of comfortable temp.
afternoon maximum temperature
average daily temperature
morning minimum temperature



RELATIVE HUMIDITY

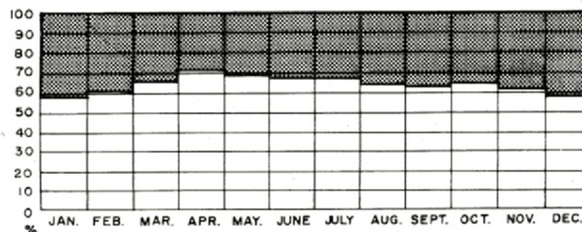
average morning humidity
average afternoon humidity
range of comfortable humidity



WIND SPEED

mean daily wind speed
wind speed for effective natural ventilation

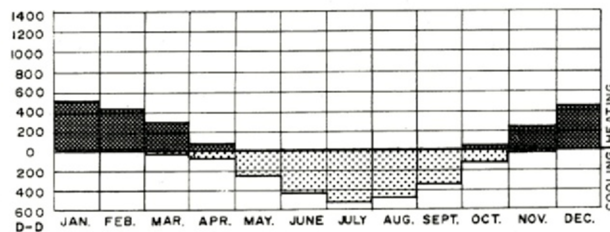
for wind direction see the wind roses on pages 42–45.



SUNSHINE
average % of daylight hours

annual sunshine = 65 %

peak solar radiation in January
horiz. sq. ft. = 900 btu/day
vert. sq. ft. = 1300 btu/day



DEGREE-DAYS

	annual
heating degree-days	1,868
cooling degree-days	2,304

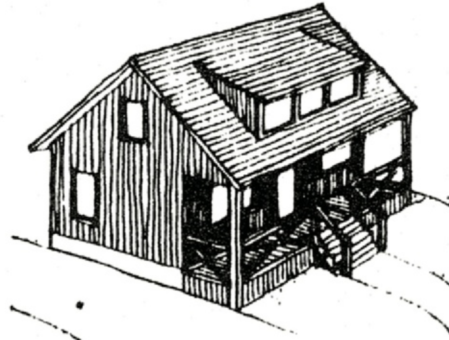
CLIMATE REGION 9

REFERENCE CITY: LITTLE ROCK, ARKANSAS

The Climate

The climate of the Mississippi Valley is similar to that of region 8, except that it is slightly more severe in both summer and winter because of the distance from the oceans. Winters are quite cold, with chilling winds from the northwest. Summers are hot and humid, with winds often from the southwest.

The annual precipitation is about 49 in. (123 cm) and occurs fairly uniformly throughout the year.

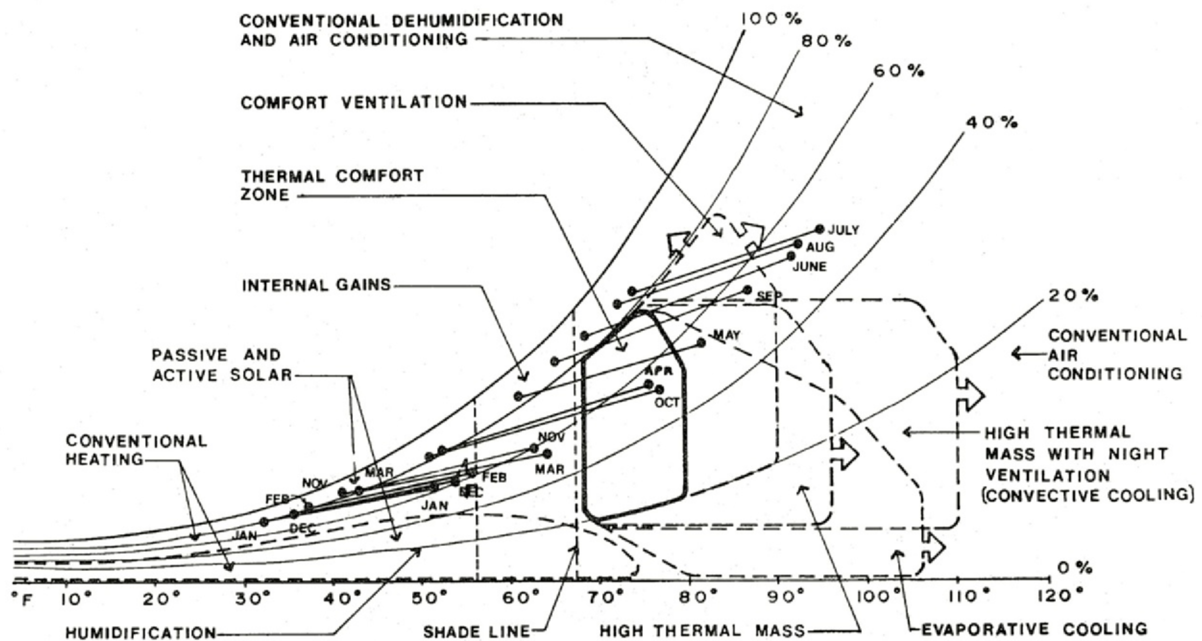


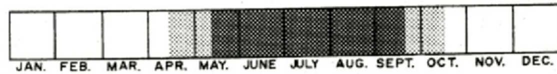


*Climatic Design Priorities**

1st Keep the heat in and cold temperatures out during the winter. (I)
2nd Let the winter sun in. (II)
3rd Use natural ventilation for summer cooling. (V)
4th Protect from the cold winter winds. (II)
5th Protect from the summer sun. (IV)
6th Avoid creating additional humidity during the summers. (X)

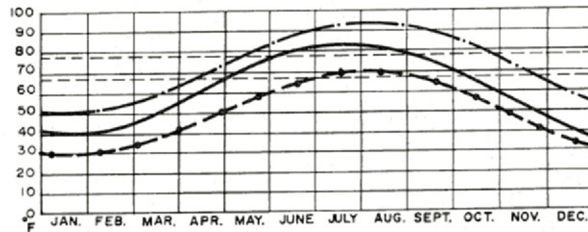
*These climatic design priorities are for envelope-dominated building types only. See Section 5.10 for a list of design strategies appropriate for achieving each of these priorities. Use the Roman numerals to find the relevant lists.





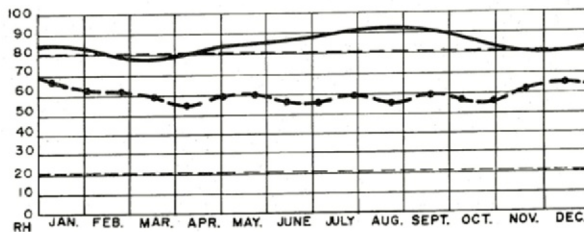
BASIC CLIMATIC CONDITION

	% of year
Comfortable period	13
too hot	35
too cold	52



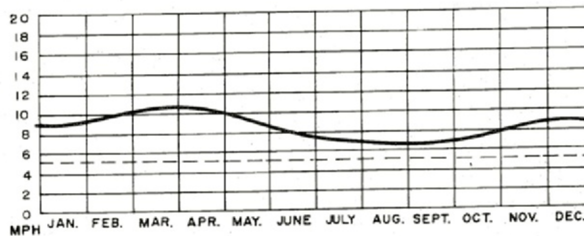
TEMPERATURE

range of comfortable temp.
afternoon maximum temperature
average daily temperature
morning minimum temperature



RELATIVE HUMIDITY

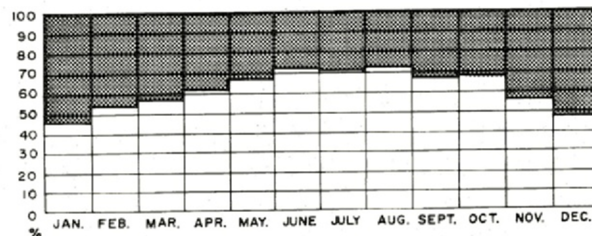
average morning humidity
average afternoon humidity
range of comfortable humidity



WIND SPEED

mean daily wind speed
wind speed for effective natural ventilation

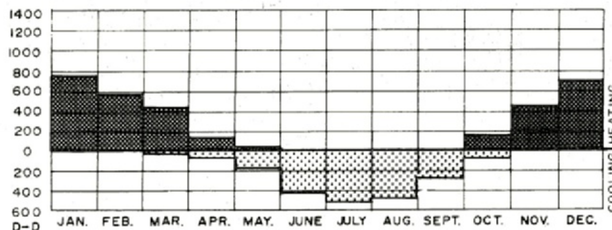
for wind direction see the wind roses on pages 42–45.



SUNSHINE
average % of daylight hours

annual sunshine = 62 %

peak solar radiation in January
horiz. sq. ft. = 600 btu/day
vert. sq. ft. = 900 btu/day

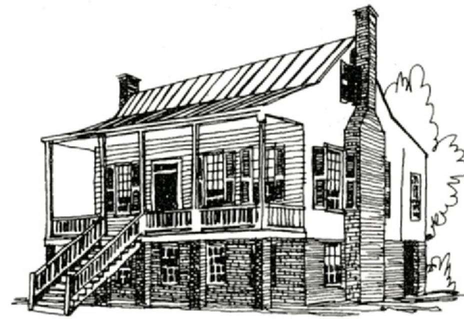


DEGREE-DAYS

	annual
heating degree-days	3,152
cooling degree-days	2,045

CLIMATE REGION 10

REFERENCE CITY: KNOXVILLE, TENNESSEE





The Climate

The climate of Appalachia is relatively temperate, with a long and pleasant spring and fall. Winters are quite cool, with a significant chilling effect from the wind. Temperatures are somewhat cooler at the northern end of this region. Snow is also more common at the northern end, although it occurs fairly frequently at higher elevations at the southern end of the region.

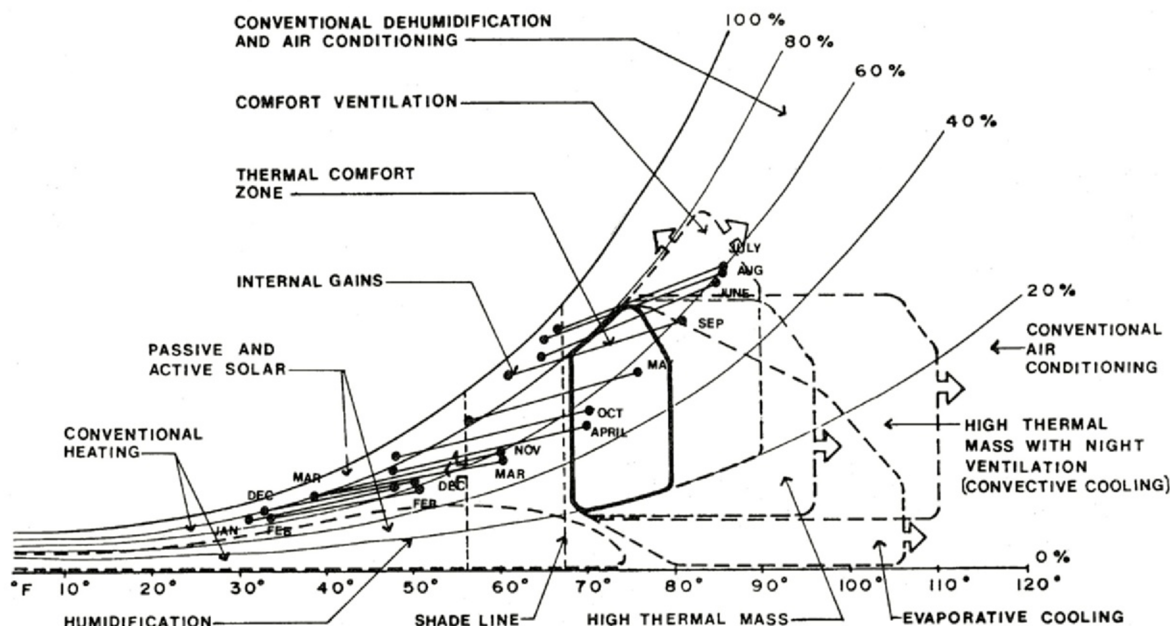
Summers are hot and somewhat humid. However, the humidity is low enough to allow a fair amount of night cooling; thus, the diurnal temperature range is fairly high. There is also a fair amount of wind available for cooling in the summer.

The annual precipitation is about 47 in. (118 cm) and occurs rather uniformly throughout the year.

*Climatic Design Priorities**

1st Keep the heat in and the cold temperatures out in the winter. (I)
2nd Use natural ventilation for summer cooling. (V)
3rd Let the winter sun in. (III)
4th Protect from the summer sun. (IV)
5th Protect from the cold winter winds. (II)
6th Avoid creating additional humidity during the summer. (X)

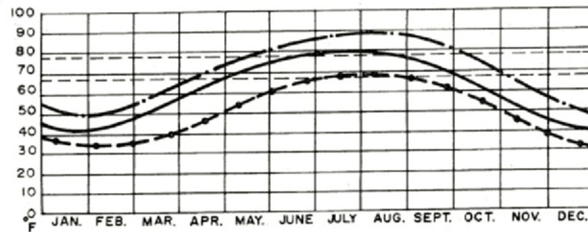
*These climatic design priorities are for envelope-dominated building types only. See Section 5.10 for a list of design strategies appropriate for achieving each of these priorities. Use the Roman numerals to find the relevant lists.





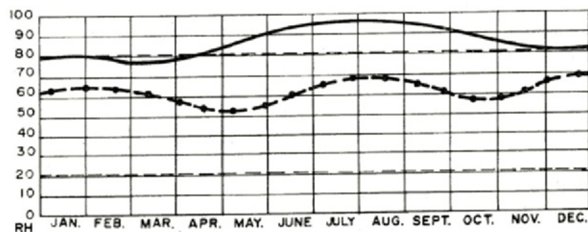
BASIC CLIMATIC CONDITION

	% of year
Comfortable period	16
too hot	28
too cold	56



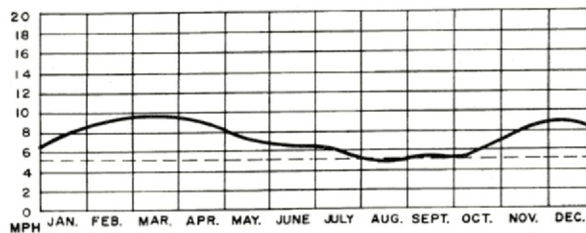
TEMPERATURE

range of comfortable temp.
afternoon maximum temperature
average daily temperature
morning minimum temperature



RELATIVE HUMIDITY

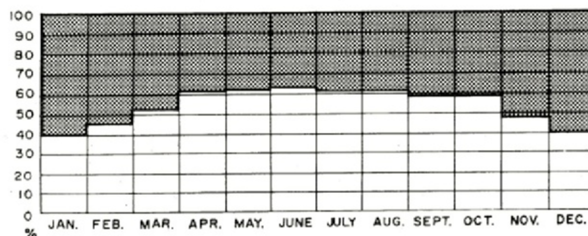
average morning humidity
average afternoon humidity
range of comfortable humidity



WIND SPEED

mean daily wind speed
wind speed for effective natural ventilation

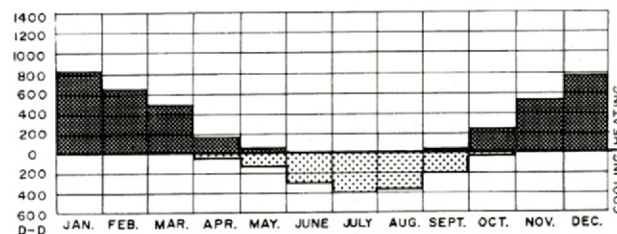
for wind direction see the wind roses on pages 42–45.



SUNSHINE
average % of daylight hours

annual sunshine = 55 %

peak solar radiation in January
horiz. sq. ft. = 600 btu/day
vert. sq. ft. = 800 btu/day



DEGREE-DAYS

	annual
heating degree-days	3,658
cooling degree-days	1,449

CLIMATE REGION 11

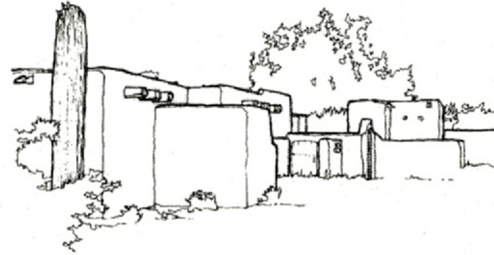
REFERENCE CITY: PHOENIX, ARIZONA

The Climate

The climate of the Southwest desert regions is characterized by extremely hot and dry summers and moderately cold winters. The skies are clear most of the year, with annual sunshine of about 85 percent.

Since summers are extremely hot and dry, the diurnal temperature range is very large; consequently, nights are quite cool. The humidity is below the comfort range much of the year. Summer overheating is the main concern for the designer.

The annual precipitation of about 7 in. (18 cm) is quite low and occurs throughout the year. April, May, and June are the driest months, while August is the wettest, with 1 in. (2.5 cm) of rain.





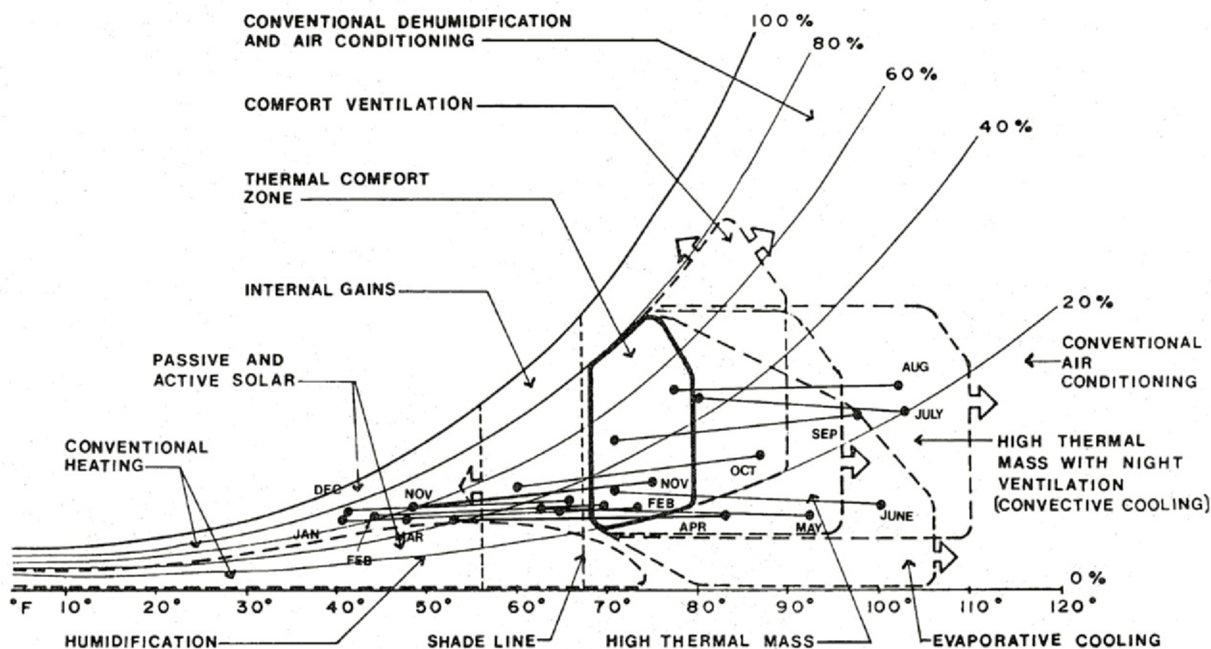
*Climatic Design Priorities**

1st Keep hot temperatures out during the summer. (VIII)
2nd Protect from the summer sun. (IV)
3rd Use evaporative cooling in the summer. (IX)
4th Use thermal mass to reduce day-to-night temperature swings during the summer. (VII)

Lower priority

5th Keep the heat in and the cool temperatures out during the winter. (I)
6th Let the winter sun in. (III)
7th Use natural ventilation to cool in the spring and fall. (VI)

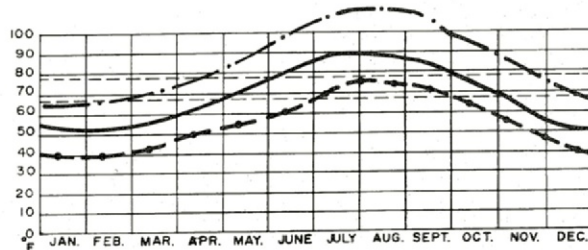
*These climatic design priorities are for envelope-dominated building types only. See Section 5.10 for a specific list of design strategies appropriate for achieving each of these priorities. Use the Roman numerals to find the relevant lists.





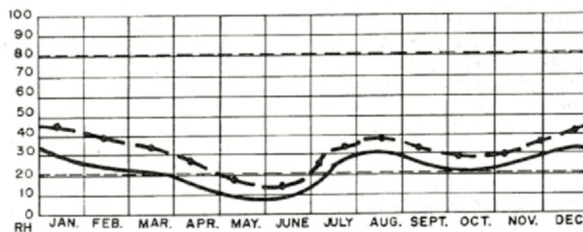
BASIC CLIMATIC CONDITION

	% of year
Comfortable period	15
too hot	37
too cold	48



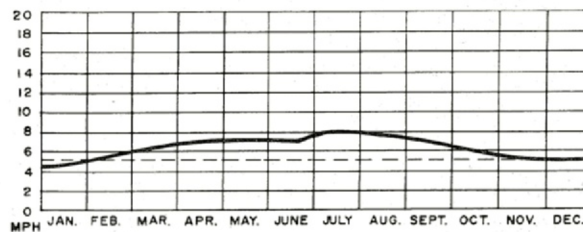
TEMPERATURE

range of comfortable temp.
afternoon maximum temperature
average daily temperature
morning minimum temperature



RELATIVE HUMIDITY

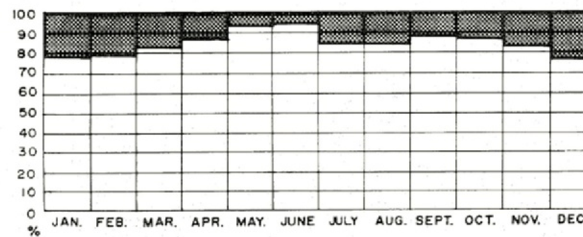
average morning humidity
average afternoon humidity
range of comfortable humidity



WIND SPEED

mean daily wind speed
wind speed for effective natural ventilation

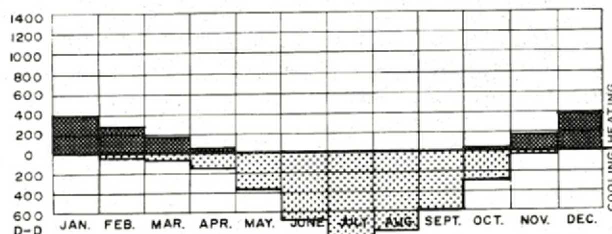
for wind direction see the wind roses on pages 42–45.



SUNSHINE
average % of daylight hours

annual sunshine = 85 %

peak solar radiation in January
horiz. sq. ft. = 1200 btu/day
vert. sq. ft. = 1600 btu/day



DEGREE-DAYS

	annual
heating degree-days	1,442
cooling degree-days	3,746

CLIMATE REGION 12

REFERENCE CITY: MIDLAND, TEXAS



The Climate

This area of west Texas and southeast New Mexico has an arid climate of hot summers and cool winters. Plentiful sunshine, more than 60 percent in the winter, can supply ample solar heating. The low humidity in summer facilitates the effective use of evaporative cooling. Thus, in this region, climatic design can have a very beneficial impact on thermal comfort.

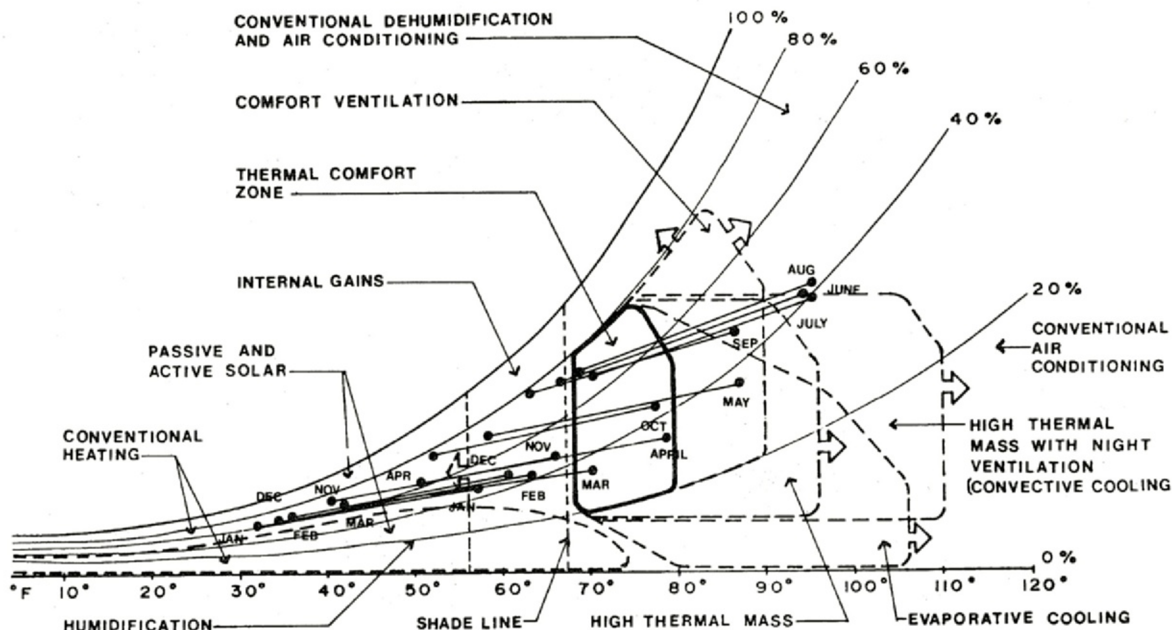
The annual precipitation is about 14 in. (35 cm), and although it occurs throughout the year, most of it falls during the summer months.

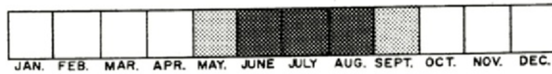


*Climatic Design Priorities**

1st Use evaporative cooling in summer. (IX)
2nd Let the winter sun in. (III)
3rd Protect from the summer sun. (IV)
4th Keep the heat in and the cool temperatures out during the winter. (I)
5th Keep hot temperatures out during the summer. (VIII)
6th Protect from the cold winter winds. (II)
7th Use natural ventilation for summer cooling. (V)
8th Use thermal mass to reduce day-to-night temperature swings during the summer. (VII).

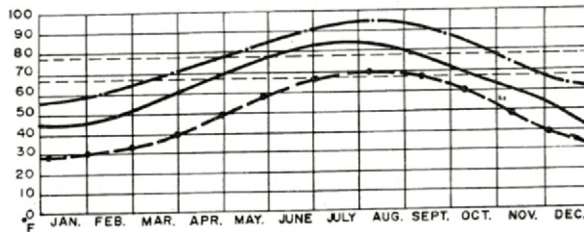
*These climatic design priorities are for envelope-dominated building types only. See Section 5.10 for a list of design strategies appropriate for achieving each of these priorities. Use the Roman numerals to find the relevant lists.





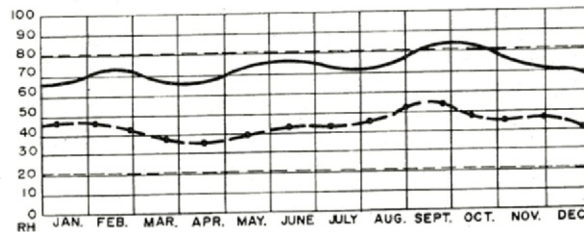
BASIC CLIMATIC CONDITION

	% of year
Comfortable period	19
too hot	26
too cold	55



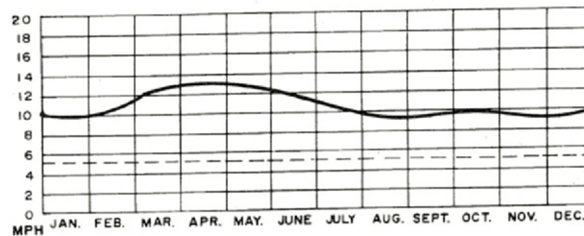
TEMPERATURE

range of comfortable temp.
afternoon maximum temperature
average daily temperature
morning minimum temperature



RELATIVE HUMIDITY

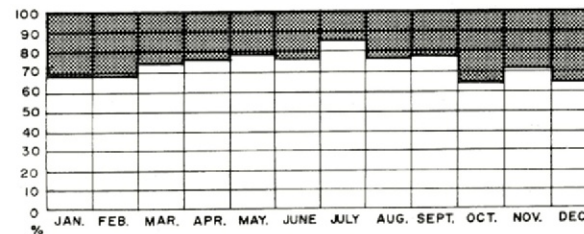
average morning humidity
average afternoon humidity
range of comfortable humidity



WIND SPEED

mean daily wind speed
wind speed for effective natural ventilation

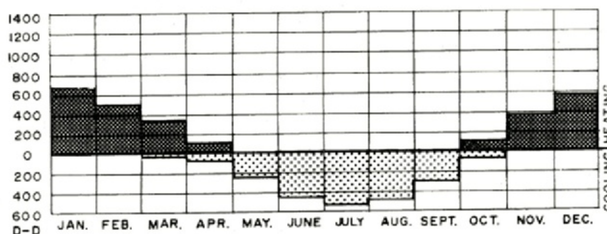
for wind direction see the wind roses on pages 42–45.



SUNSHINE
average % of daylight hours

annual sunshine = 74 %

peak solar radiation in January
horiz. sq. ft. = 1100 btu/day
vert. sq. ft. = 1450 btu/day



DEGREE-DAYS

	annual
heating degree-days	2658
cooling degree-days	2,126

CLIMATE REGION 13

REFERENCE CITY: FORT WORTH, TEXAS





The Climate

This area of Oklahoma and north Texas has cold winters and hot summers. Cold winds come from the north and northeast. There is a significant amount of sunshine available for winter solar heating.

During part of the summer, the high temperatures and fairly high humidity combine to create uncomfortable conditions. During other times in the summer, the humidity drops sufficiently to enable evaporative cooling to work. There are also ample summer winds for natural ventilation.

During the drier parts of the summer and especially during spring and fall, the diurnal temperature range is large enough to encourage the use of thermal mass. The annual precipitation is about 29 in. (73 cm) and occurs fairly uniformly throughout the year.

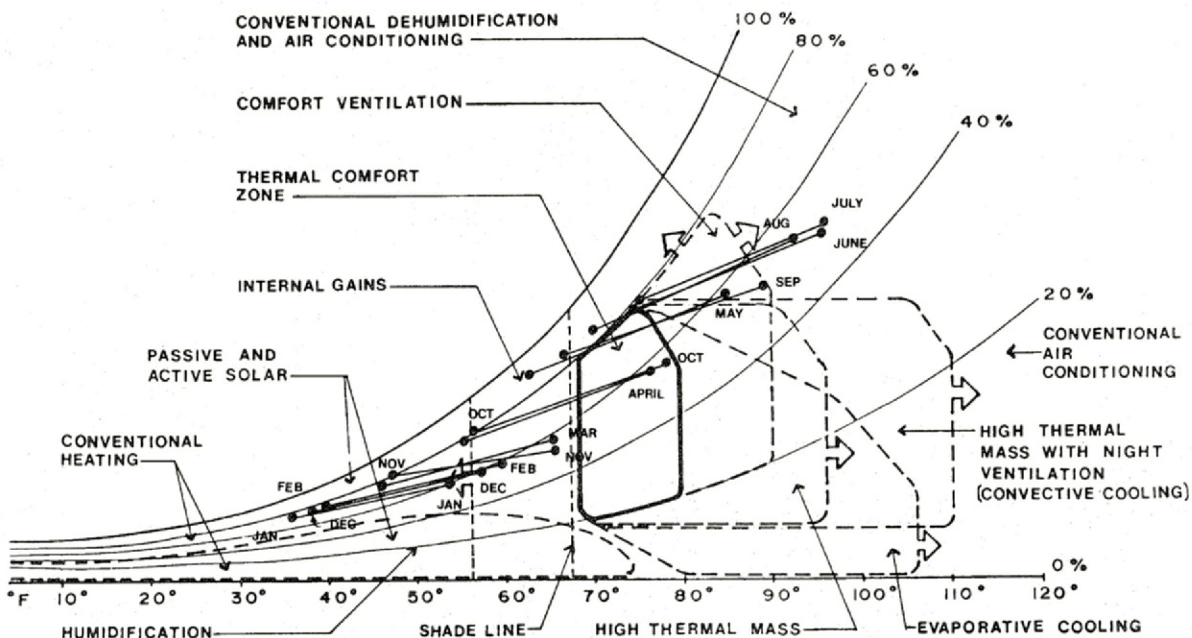
*Climatic Design Priorities**

1st Use natural ventilation for cooling in spring and fall. (V)
2nd Let the winter sun in. (III)
3rd Protect from the summer sun. (IV)
4th Protect from the cold winter winds. (II)

Lower priority

5th Use thermal mass to reduce day-to-night temperature swings during the summer. (VII)

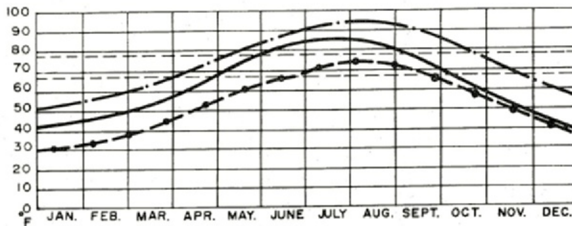
*These climatic design priorities are for envelope-dominated building types only. See Section 5.10 for a list of design strategies appropriate for achieving each of these priorities. Use the Roman numerals to find the relevant lists.





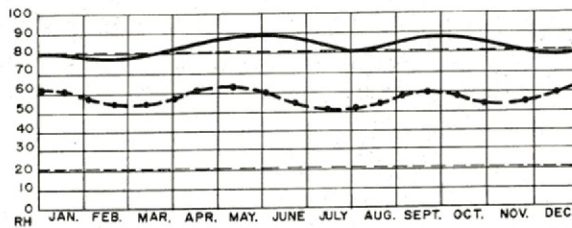
BASIC CLIMATIC CONDITION

	% of year
Comfortable period	14
too hot	39
too cold	47



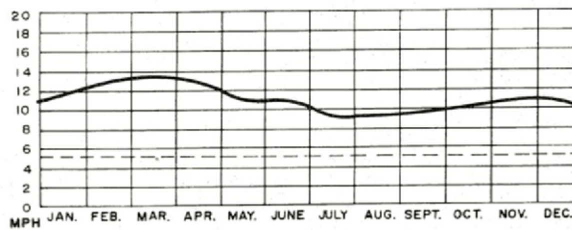
TEMPERATURE

range of comfortable temp.
afternoon maximum temperature
average daily temperature
morning minimum temperature



RELATIVE HUMIDITY

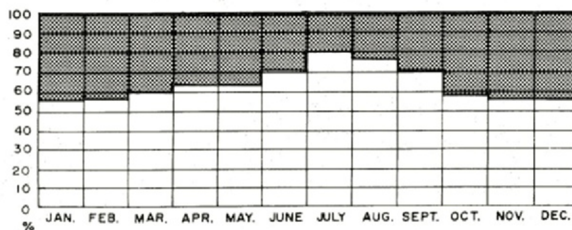
average morning humidity
average afternoon humidity
range of comfortable humidity



WIND SPEED

mean daily wind speed
wind speed for effective natural ventilation

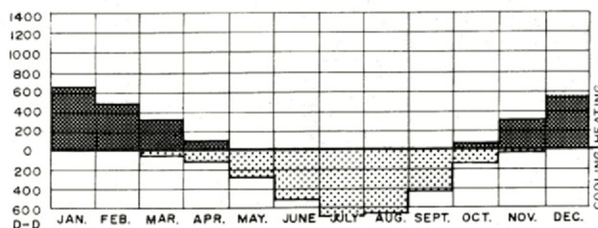
for wind direction see the wind roses on pages 42–45.



SUNSHINE
average % of daylight hours

annual sunshine = 64 %

peak solar radiation in January
horiz. sq. ft. = 900 btu/day
vert. sq. ft. = 1200 btu/day

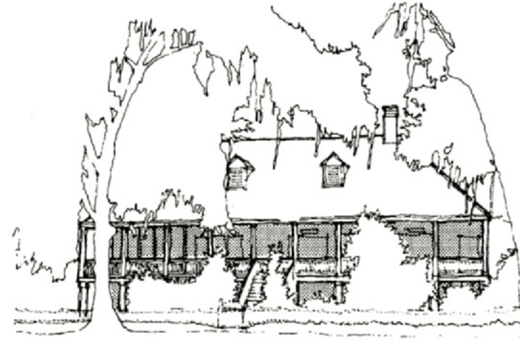


DEGREE-DAYS

	annual
heating degree-days	2,407
cooling degree-days	2,809

CLIMATE REGION 14

REFERENCE CITY: NEW ORLEANS, LOUISIANA



The Climate

This Gulf Coast region has cool but short winters. Summers, on the other hand, are hot, very humid, and long. The flat, damp ground and frequent rains create a very humid climate. Besides creating thermal discomfort, the high humidity causes mildew problems. Much of the region has reliable sea breezes, which are strongest during the day, weaker at night, and nonexistent during the morning and evening when the wind reverses direction.

The annual precipitation is quite high at 60 in. (150 cm) and occurs fairly uniformly throughout the year.



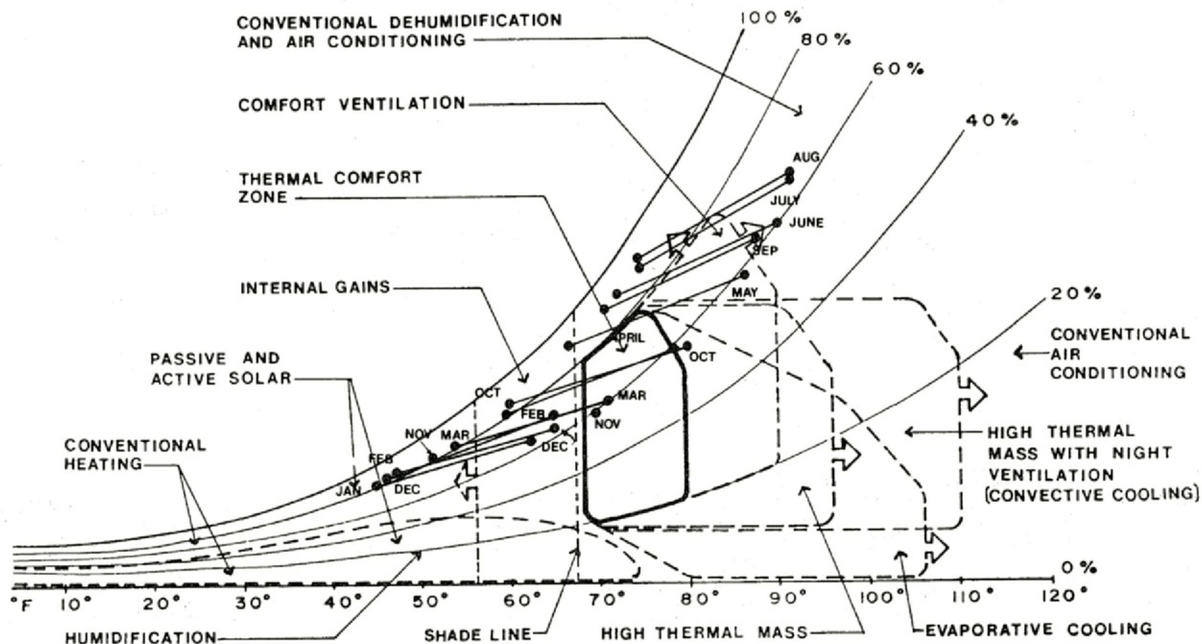
*Climatic Design Priorities**

1st Allow natural ventilation to both cool and remove excess moisture in the summer. (VI)
2nd Protect from the summer sun. (IV)
3rd Avoid creating additional humidity during the summer. (X)

Lower priority

4th Let the winter sun in. (III)
5th Protect from the cold winter winds. (II)

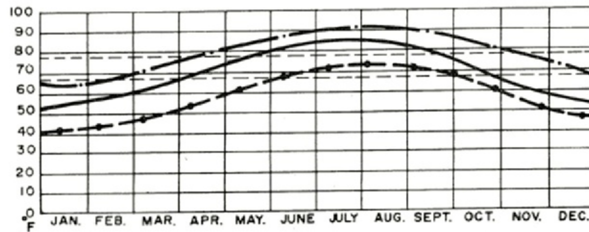
*These climatic design priorities are for envelope-dominated building types only. See Section 5.10 for a list of design strategies appropriate for achieving each of these priorities. Use the Roman numerals to find the relevant lists.





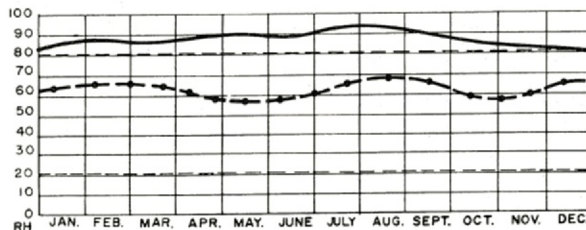
BASIC CLIMATIC CONDITION

	% of year
Comfortable period	12
too hot	52
too cold	36



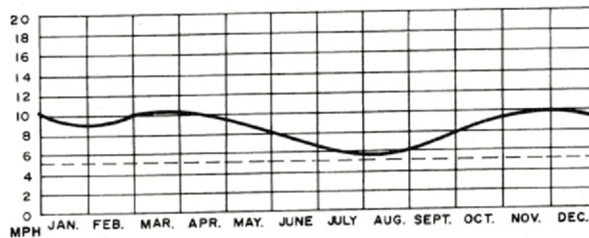
TEMPERATURE

range of comfortable temp.
afternoon maximum temperature
average daily temperature
morning minimum temperature



RELATIVE HUMIDITY

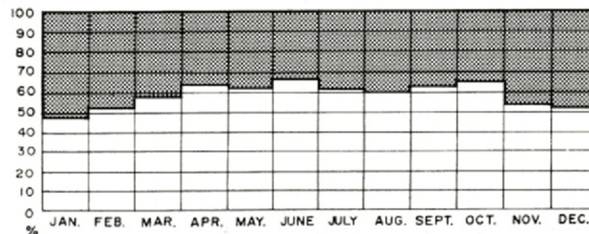
average morning humidity
average afternoon humidity
range of comfortable humidity



WIND SPEED

mean daily wind speed
wind speed for effective natural ventilation

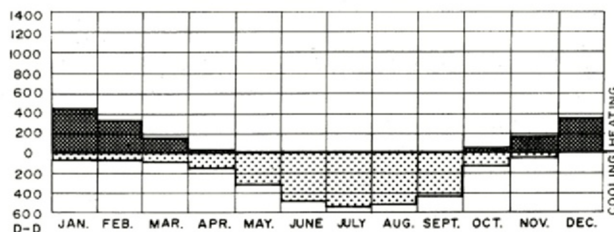
for wind direction see the wind roses on pages 42–45.



SUNSHINE
average % of daylight hours

annual sunshine = 59 %

peak solar radiation in January
horiz. sq. ft. = 800 btu/day
vert. sq. ft. = 1250 btu/day



DEGREE-DAYS

	annual
heating degree-days	1,490
cooling degree-days	2,686

CLIMATE REGION 15

REFERENCE CITY: HOUSTON, TEXAS

The Climate

This part of the Gulf Coast is similar to region 14 except that the summers are more severe. Very high temperatures and humidity levels make this a very uncomfortable summer climate. The high humidity and clouds prevent the temperature from dropping much at night. Thus, the diurnal temperature range is quite small. Fortunately, frequent coastal breezes exist in the summer.

Winters are short and mild. Ample sunshine can supply most of the winter heating demands, but the main concern for the designer is summer overheating.

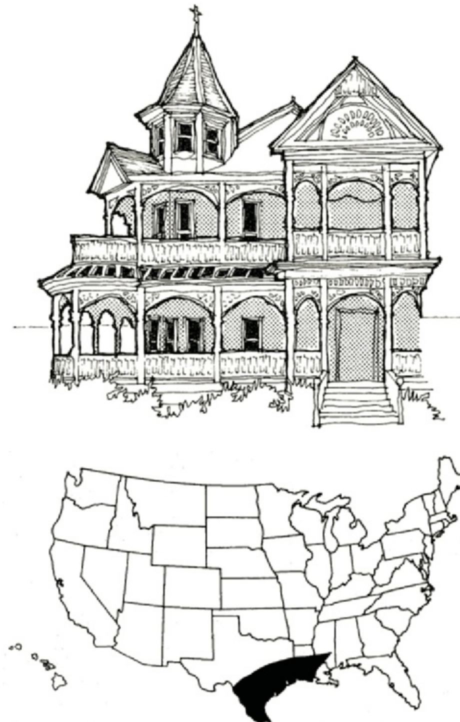
The annual precipitation is about 45 in. (113 cm) and occurs fairly uniformly throughout the year.

*Climatic Design Priorities**

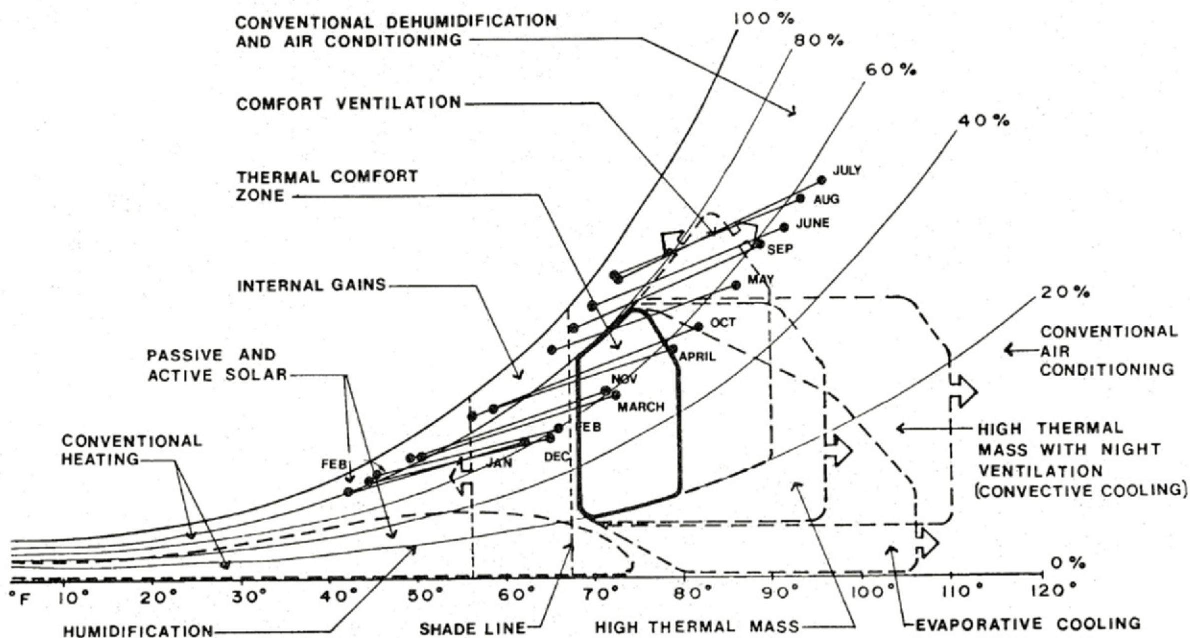
1st Keep hot temperatures out during the summer. (VIII)
2nd Allow natural ventilation to both cool and remove excess moisture in the summer. (VI)
3rd Protect from the summer sun. (IV)
4th Avoid creating additional humidity during the summer. (X)

Lower priority

5th Protect from the cold winter winds. (II)
6th Let the winter sun in. (III)
7th Keep the heat in and the cool temperatures out during the winter. (I)



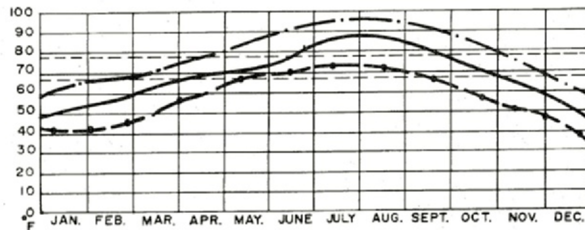
*These climatic design priorities are for envelope-dominated building types only. See Section 5.10 for a list of design strategies appropriate for achieving each of these priorities. Use the Roman numerals to find the relevant lists.





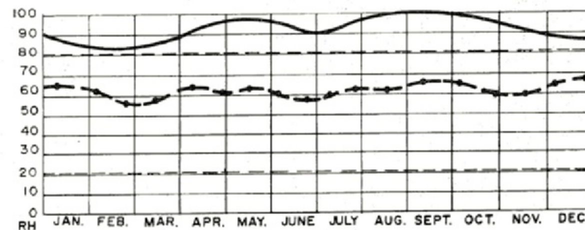
BASIC CLIMATIC CONDITION

	% of year
Comfortable period	11
too hot	54
too cold	35



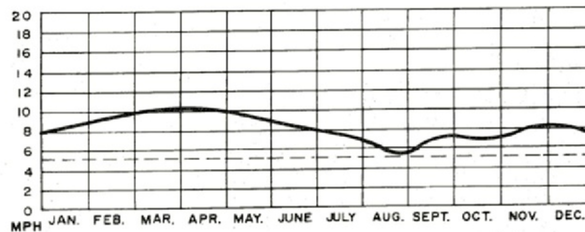
TEMPERATURE

range of comfortable temp.
afternoon maximum temperature
average daily temperature
morning minimum temperature



RELATIVE HUMIDITY

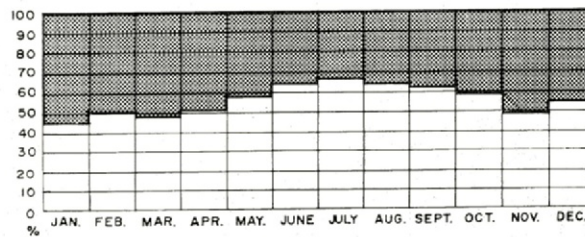
average morning humidity
average afternoon humidity
range of comfortable humidity



WIND SPEED

mean daily wind speed
wind speed for effective natural ventilation

for wind direction see the wind roses on pages 42–45.

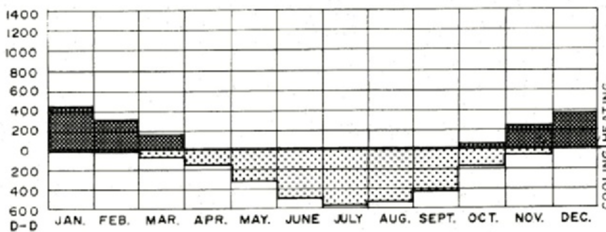


SUNSHINE

average % of daylight hours

annual sunshine = 56 %

peak solar radiation in January
horiz. sq. ft. = 1050 btu/day
vert. sq. ft. = 1300 btu/day

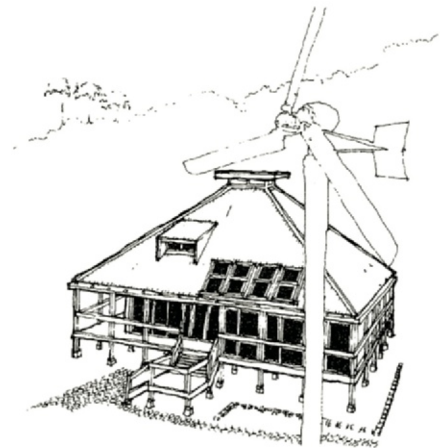


DEGREE-DAYS

	annual
heating degree-days	1,549
cooling degree-days	2,761

CLIMATE REGION 16

REFERENCE CITY: MIAMI, FLORIDA





The Climate

The climate of southern Florida has long, hot summers and no winters. When the slightly high temperatures are combined with high humidity, uncomfortable summers are the result. However, in spring, fall, and winter, the climate is quite pleasant. Ocean winds add significantly to year-round comfort.

The annual precipitation is quite high at about 58 in. (145 cm), and much of the rain falls during the summer months.

*Climatic Design Priorities**

1st Open the building to the outdoors since temperatures are comfortable much of the year. (XI)

2nd Protect from the summer sun. (IV)

3rd Allow natural ventilation to both cool and remove excess moisture most of the year. (VI)

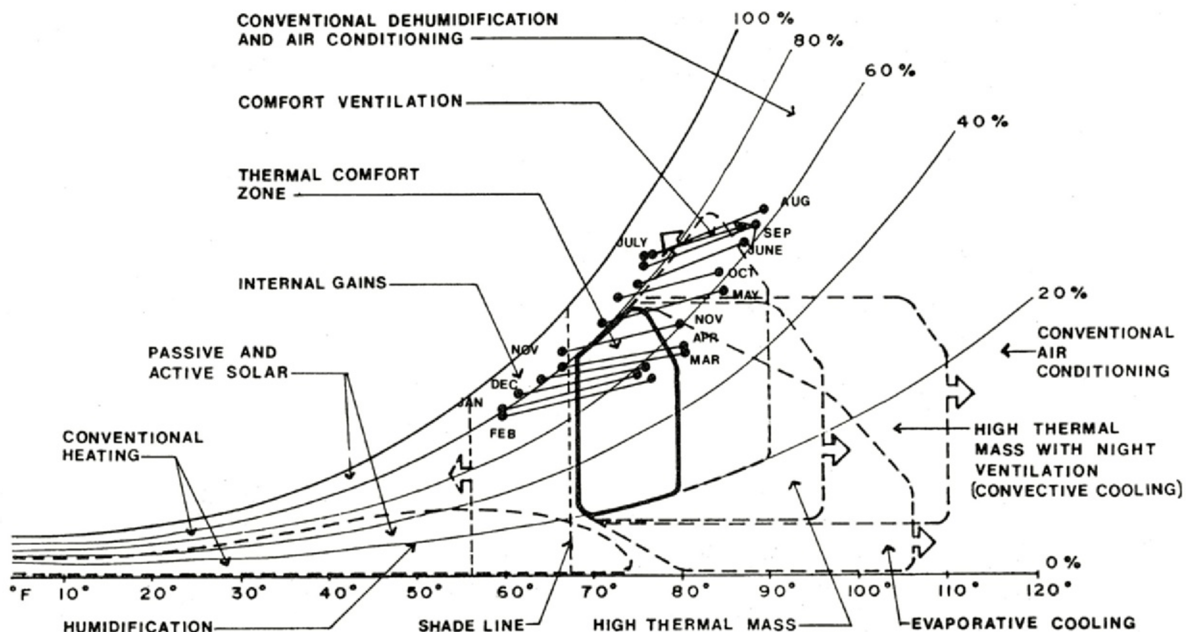
4th Avoid creating additional humidity. (X)

Lower priority

5th Keep the hot temperatures out during the summer. (VIII)

6th Keep the heat in and the cool temperatures out during the winter. (I)

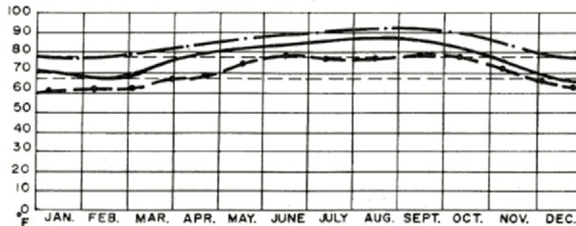
*These climatic design priorities are for envelope-dominated building types only. See Section 5.10 for a list of design strategies appropriate for achieving each of these priorities. Use the Roman numerals to find the relevant lists.





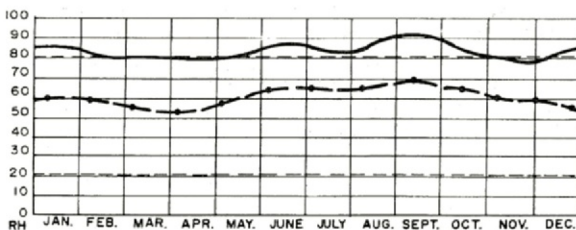
BASIC CLIMATIC CONDITION

		% of year
	Comfortable period	20
	too hot	69
	too cold	11



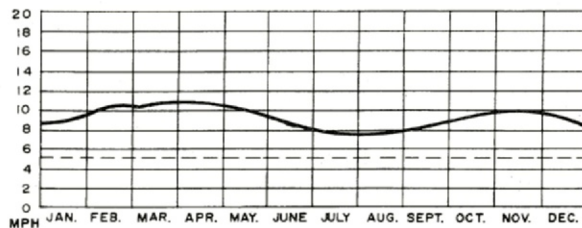
TEMPERATURE

- range of comfortable temp.
- afternoon maximum temperature
- average daily temperature
- morning minimum temperature



RELATIVE HUMIDITY

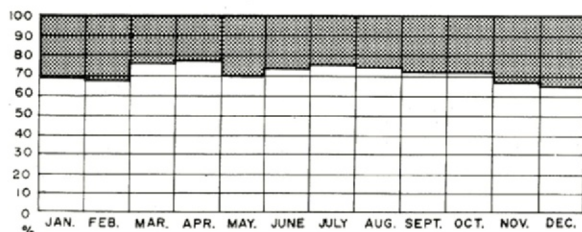
- average morning humidity
- average afternoon humidity
- range of comfortable humidity



WIND SPEED

- mean daily wind speed
- wind speed for effective natural ventilation

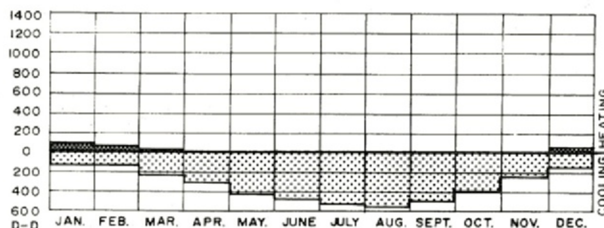
for wind direction see the wind roses on pages 42–45.



SUNSHINE
average % of daylight hours

annual sunshine = 72 %

peak solar radiation in January
horiz. sq. ft. = 1300 btu/day
vert. sq. ft. = 1450 btu/day

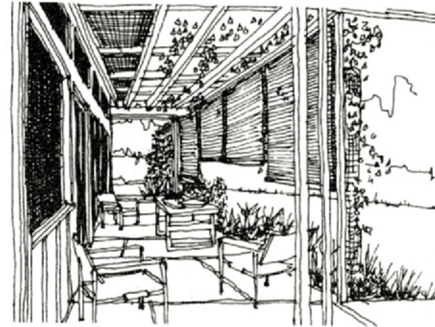


DEGREE-DAYS

		annual
	heating degree-days	199
	cooling degree-days	4,095

CLIMATE REGION 17

REFERENCE CITY: LOS ANGELES, CALIFORNIA





The Climate

The semiarid climate of Southern California is very mild because of the almost constant cool winds from the ocean. Although these onshore winds bring high humidity, comfort is maintained because of the low temperatures.

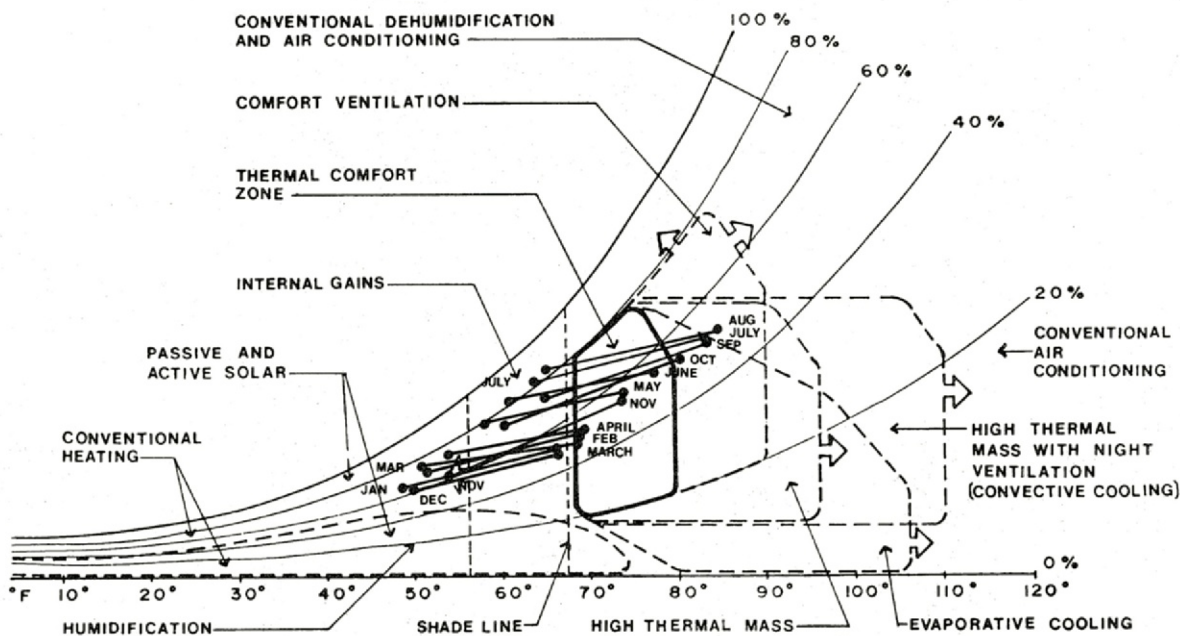
Occasionally when the wind reverses, hot desert air enters the region. Because this air is dry, comfort is still maintained. There is a sharp increase in temperature and a decrease in humidity as one leaves the coast. Thus, a large variation in the local microclimates exists.

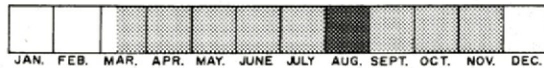
Winter temperatures are very moderate, and little heating is required. Although the annual precipitation of about 15 in. (38 cm) is not very low, the rain falls mainly in the winter. Since there is almost no rain during the summer, few plants can grow year-round without irrigation. Because sunshine is plentiful all year, solar heating, especially for hot water, is very advantageous.

*Climatic Design Priorities**

1st Open the building to the outdoors since temperatures are comfortable most of the year. (XI)
2nd Protect from the summer sun. (IV)
3rd Let the winter sun in. (III)
4th Use natural ventilation for summer cooling. (V)
5th Use thermal mass to reduce day-to-night temperature swings in the summer. (VII)

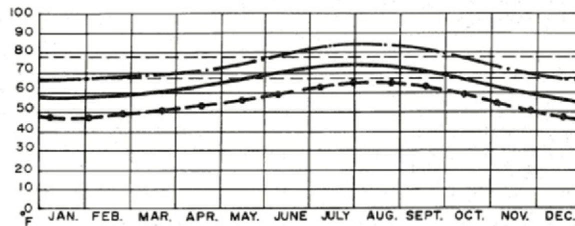
*These climatic design priorities are for envelope-dominated building types only. See Section 5.10 for a list of design strategies appropriate for achieving each of these priorities. Use the Roman numerals to find the relevant lists.





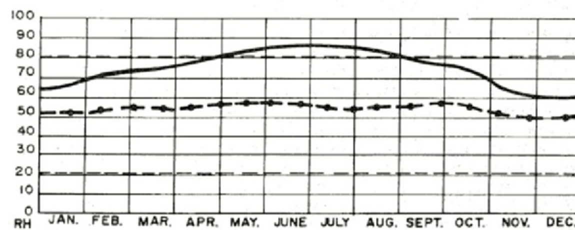
BASIC CLIMATIC CONDITION

	% of year
Comfortable period	64
too hot	8
too cold	28



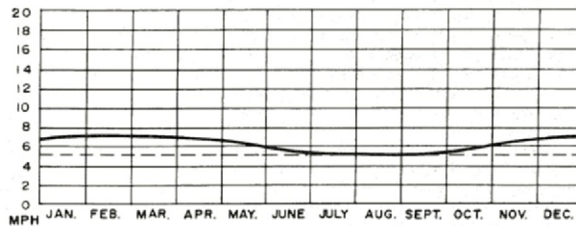
TEMPERATURE

- range of comfortable temp.
- afternoon maximum temperature
- average daily temperature
- morning minimum temperature



RELATIVE HUMIDITY

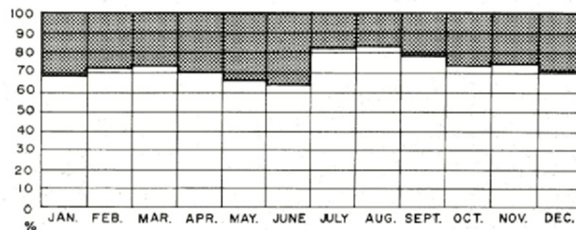
- average morning humidity
- average afternoon humidity
- range of comfortable humidity



WIND SPEED

- mean daily wind speed
- wind speed for effective natural ventilation

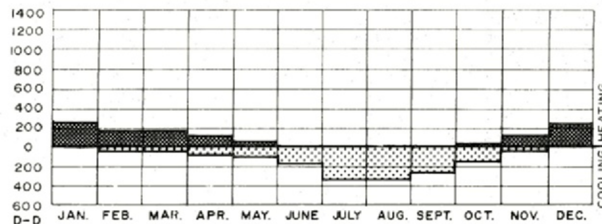
for wind direction see the wind roses on pages 42–45.



SUNSHINE
average % of daylight hours

annual sunshine = 73 %

peak solar radiation in January
horiz. sq. ft. = 900 btu/day
vert. sq. ft. = 1200 btu/day



DEGREE-DAYS

	annual
heating degree-days	1,204
cooling degree-days	1,339

5.10 DESIGN STRATEGIES

The following climate-related design strategies are appropriate ways of achieving the design priorities listed in the Climatic Data Tables (above). More detailed information is found in the chapters shown in parentheses.

Winter

I. Keep the heat in and the cold temperatures out during the winter. (Fig. 5.10a).
   a. Avoid building on cold northern slopes. (Chapter 11)
   b. Build on the middle of slopes to avoid both the pools of cold air at the bottom and the high winds at the top of hills. (Chapter 11)
   c. Use a compact design with a minimum surface-area-to-volume ratio. For example, use two- instead of one-story buildings. (Chapter 15)
   d. Build attached or clustered buildings to minimize the number of exposed walls. (Chapter 15)
   e. Use earth sheltering in the form of underground or bermed structures. (Chapter 15)
   f. Place buffer spaces that have lower temperature requirements (closets, storage rooms, stairs, garages, gymnasiums, heavy work areas, etc.) along the north wall. Place a sunspace buffer room on the south wall. (Chapters 7 and 15)
   g. Use temperature zoning by both space and time since some spaces can be kept cooler than others at all times or at certain times. For example, bedrooms can often be kept cooler during the day and especially during the night. (Chapter 16)
   h. Minimize the window area on all orientations except south. (Chapters 7 and 15)
   i. Use double or triple glazing, low-e coatings, and movable insulation on windows. (Chapter 15)
   j. Use plentiful insulation in walls, on roofs, under floors, over crawl spaces, on foundation walls, and around slab edges. (Chapter 15)
   k. Insulation should be a continuous envelope to prevent heat bridges. Avoid structural elements that are exposed on the exterior, since they pierce the insulation. Avoid fireplaces and other masonry elements that penetrate the insulation layer. (Chapter 15)
   l. Place doors on fireplaces to prevent heated room air from escaping through the chimney. Supply fireplaces and stoves with outdoor combustion air. (Chapter 16)

II. Protect from the cold winter winds (Fig. 5.10b).
   a. Avoid windy locations, such as hilltops. (Chapter 11)
   b. Use evergreen vegetation to create windbreaks. (Chapter 11)
   c. Use garden walls to protect the building and especially entrances from cold winds. (Chapter 11)
   d. In very windy areas, keep buildings close to the ground (one story).
   e. Use compact designs to minimize the surface area exposed to the wind. (Chapter 15)
   f. Use streamlined shapes with rounded corners to both deflect the wind and minimize the surface-area-to-volume ratio.
   g. Cluster buildings for mutual wind protection. (Chapter 11)
   h. Use long-sloping roofs, as in the New England saltbox houses, to deflect the wind over the building and to create sheltered zones on the sunny side.
   i. Place garages and other utility spaces on the winter windward side. This is usually the north, northwest, and northeast side of the building.
   j. Use sunspaces and glazed-in porches as windbreaks.

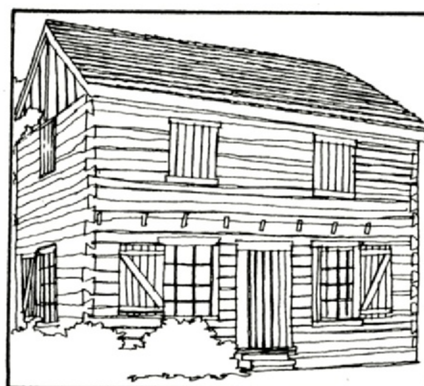
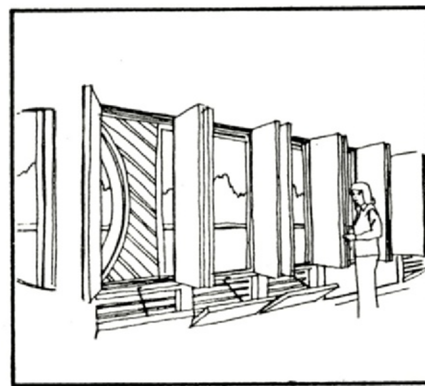




Figure 5.10a Use attached buildings to reduce the exposed wall area. Use compact building forms and two-story plans. Use at least double glazing. Always use low-e glazing, and consider using movable night insulation. (Drawings from *Regional Guidelines for Building Passive Energy Conserving Homes* by the AIA Research Corporation.)

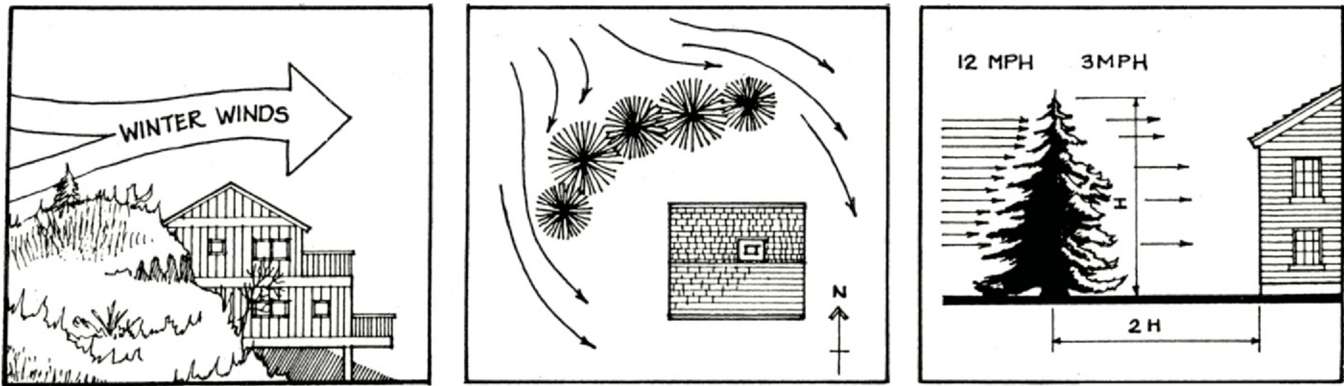


Figure 5.10b Build in wind-protected areas such as the side of a hill. Plant or build barriers against the wind. Evergreen trees are effective wind barriers. (Drawings from *Regional Guidelines for Building Passive Energy Conserving Homes* by the AIA Research Corporation.)

k. Use earth sheltering. Also, the wind can be deflected by earth berms built against the wall or by constructing protective earth banks a short distance from the building. (Chapters 11 and 15)
l. Minimize openings, especially on the side facing the winter winds, and place the main entry on the leeward side. (Chapter 15)
m. Use storm windows, storm doors, air locks (vestibules), and revolving doors to minimize infiltration. (Chapter 15)
n. Close all attic and crawl-space vents, but see Chapter 15 for precautions against the hazards of water vapor and radon gas.
o. Use tight construction, caulking, weather stripping, and air (wind) barriers to minimize infiltration. Use high-quality operable windows and doors. (Chapter 15)
p. Place outdoor courtyards on the south side of the building. (Chapter 11)
q. In winter, even windows in freestanding garden walls should be closed to protect the enclosure from cold winds.
r. In snow country, use snow fences and windscreens to keep snow from blocking entries and south-facing windows.

III. Let the winter sun in (covered in Chapter 7 unless noted otherwise) (Fig. 5.10c).

a. Build on south, southeast, or southwest slopes. (Chapter 11)
b. Check for solar access that might be blocked by landforms, vegetation, and man-made structures. (Chapter 11)
c. Avoid trees on the south side of the building. (Chapter 11)
d. Use only deciduous trees on the southeast and southwest sides.
e. Use deciduous trees on the east and west sides if winter is very long and wind is not a problem.
f. The long axis of the building should run east–west.
g. Most windows should face south.
h. Use south-facing clerestories and dormers instead of skylights.

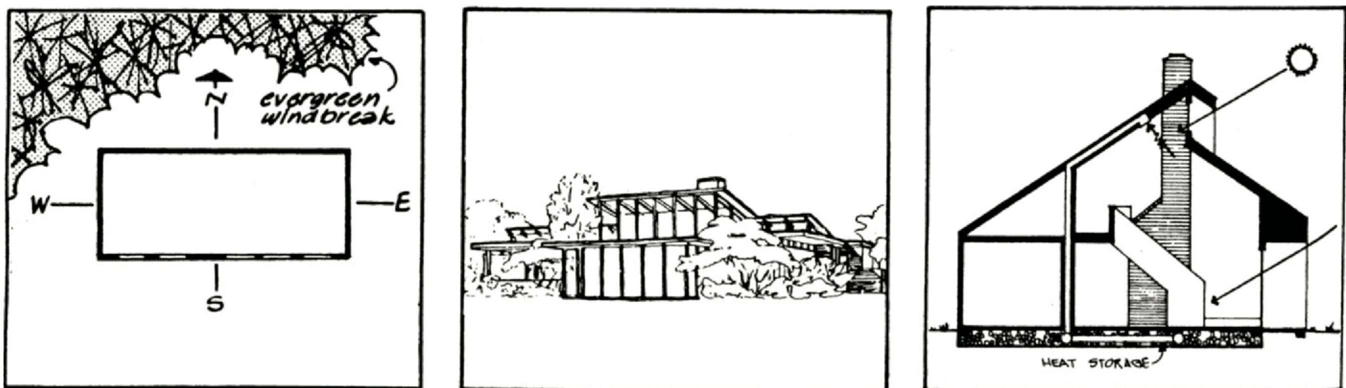


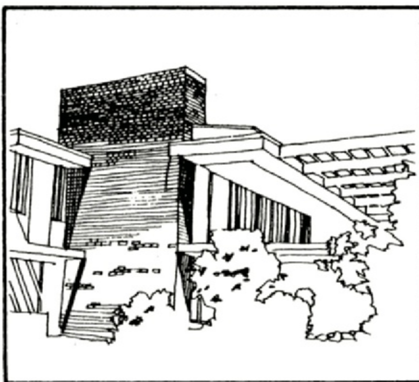
Figure 5.10c Orient the building with the long side facing south. Avoid trees or other structures on the south side. Place most windows on the south facade. Use mainly vertical glazing. Use south-facing clerestory windows or dormers to bring the sun farther into the interior. (Drawings from *Regional Guidelines for Building Passive Energy Conserving Homes* by the AIA Research Corporation.)

i. Place spaces that benefit the most from solar heating along the south wall. Spaces that benefit the least should be along the north wall (e.g., storage rooms, garages). (Chapter 15)
j. Use an open floor plan to enable sun and sun-warmed air to penetrate throughout the building.
k. Use direct-gain, Trombe walls, and sunspaces for effective passive solar heating.
l. Use thermal mass on the interior to absorb and store solar radiation.
m. Use light-colored patios, pavements, or land surfaces to reflect additional sunlight through windows.
n. Use specular reflectors (polished aluminum) to reflect additional sunlight through windows.
o. Use active solar collectors for domestic hot water, swimming-pool heating, space heating, and process heat for industry. (Chapter 8)
p. If there is little or no summer overheating, use dark colors on exterior walls (especially the south wall).
q. Create sunny but wind-protected outdoor spaces on the south side of the building. (Chapter 11)

Summer

IV. Protect from the summer sun (covered in Chapter 9 unless noted otherwise) (Fig. 5.10d).

a. Avoid building on east and especially west slopes. North slopes are best if solar heating is not required in the winter, while south slopes are best if solar heating is desirable in the winter. (Chapter 11)
b. Use plants for shading. Evergreen trees can be used on the east, west, and north sides of a building. Deciduous plants are most appropriate for shading the southeast, the southwest, and the roof. Unless carefully placed, deciduous plants on the south side of a building might do more harm in the winter than good in the summer. The exception is a very hot climate with a very mild winter. (Chapter 11)
c. Avoid light-colored ground covers around the building to minimize reflected light entering windows unless daylighting is an important strategy. Living ground covers are best because they do not heat the air while they absorb solar radiation.
d. Have neighboring buildings shade each other. Tall buildings with narrow alleys between them work best. (Chapter 11)
e. Protect against reflections from adjacent structures that have white walls or, especially, reflective glazing.
f. Build attached houses or clusters to minimize the number of exposed walls. (Chapter 15)
g. Use freestanding or wing walls to shade the east, west, and north walls.
h. Use the form of the building to shade itself (e.g., cantilever floors, balconies, courtyards).
i. Avoid east and especially west windows if at all possible. Minimize the size and number of any east and west windows that are necessary. Design east and west facades so that windows face in a northerly or southerly direction (e.g. sawtooth facade).
j. Use only vertical glazing! Any horizontal or sloped glazing (skylights) should be shaded on the outside during the summer. Only skylights on steep northern roofs do not require exterior shading.
k. Use exterior shading devices on all windows except north windows in cool climates.
l. Shade not only windows but also east and especially west walls. In very hot climates, also shade the south and north walls.
m. Use a double or second roof (ice house roof), with the



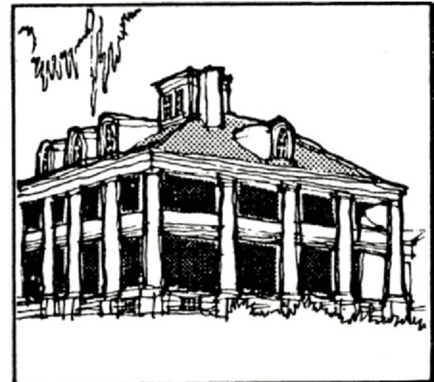


Figure 5.10d Orient the short side of the building to the east and west and avoid windows on these facades if possible. Use overhangs, balconies, and porches to shade both windows and walls. Use large overhanging roofs and porticoes to shade both windows and walls. (Drawings from *Regional Guidelines for Building Passive Energy Conserving Homes* by the AIA Research Corporation.)



Figure 5.10e Provide many large but shaded windows for ventilation. Provide both high and low openings. Provide large openings to vent attic spaces. (Drawings from *Regional Guidelines for Building Passive Energy Conserving Homes* by the AIA Research Corporation.)

space between the roofs well ventilated. Use a parasol roof.

n. Use shaded outdoor spaces, such as porches and carports, to protect the east and, especially, west facades, as well as south walls in climates with mild winters.

o. Use louvered rather than solid shading devices to prevent trapping hot air next to the windows.

p. Use vines on walls and/or trellises for shading. (Chapters 9 and 11)

q. Use movable shading devices that can retract to allow full winter sun penetration and on cloudy summer days for more daylight.

r. Use highly reflective building surface (white is best). The roof and west wall are the most critical.

s. Use interior shading devices in addition to exterior shading devices.

t. Use low solar heat gain glazing on east and west windows but only on south windows if winter heat is not needed.

u. Place outdoor courtyards that are intended for summer use on the north side of the building. The east side is the next best choice. (Chapter 11)

V. Use natural ventilation for summer cooling (covered in Chapter 10 unless noted otherwise) (Fig. 5.10e).

a. Use night ventilation to cool the building in preparation for the next day. Called night-flush cooling, this is described under priority VII below.

b. Use comfort ventilation, natural ventilation that cools people by passing air over their skin.

c. Site and orient the building to capture the prevailing winds. (Chapters 10 and 11)

d. Direct and channel winds toward the building by means of landscaping and landforms. (Chapter 11)

e. Keep buildings far enough apart to allow full access to the desirable winds. (Chapter 11)

f. In mild climates where winters are not very cold and summer temperatures are not extremely high, use a noncompact shape for maximum cross ventilation.

g. Elevate the main living space since wind velocity increases with the height above ground.

h. Use high ceilings, two-story spaces, and open stairwells for vertical air movement and for the benefits of stratification.

i. Provide cross ventilation by using large windows on both the windward and leeward sides of the building.

j. Use fin walls to direct air through the windows.

k. Use a combination of high and low openings to take advantage of the stack effect.

l. Use roof openings to vent both the attic and the whole building. Use openings, such as monitors, cupolas, dormers, roof turrets, ridge vents, gable vents, and soffit vents.

m. Use porches to create cool outdoor spaces and to protect open windows from sun and rain.

n. Use a double or parasol roof with sufficient clearance to allow the wind to ventilate the hot air collecting between the two roofs. (Chapter 9)

o. Use high-quality operable windows with good seals to allow summer ventilation while preventing winter infiltration. (Chapter 15)

p. Use an open floor plan for maximum airflow. Minimize the use of partitions.

q. Keep transoms and doors open between rooms.

r. Use a solar chimney to move air vertically through a building even on calm, sunny days.

s. Use operable windows or movable panels in garden walls to maximize the summer ventilation of a site while allowing protection against the winter winds.

VI. Allow natural ventilation to both cool and remove excess moisture in the summer (covered

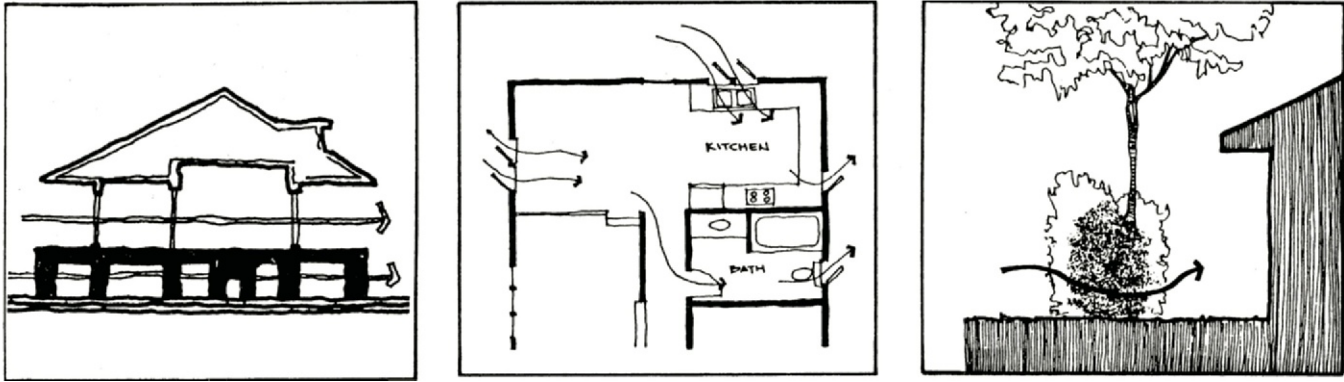


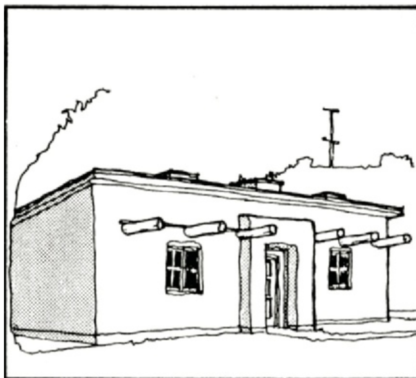
Figure 5.10f Raise the building above the moisture at ground level and ventilate under the building. Allow natural ventilation to carry away moisture from kitchens, bathrooms, and laundry rooms. Avoid dense landscaping near ground level, but a high canopy of trees is good. (Drawings from *Regional Guidelines for Building Passive Energy Conserving Homes* by the AIA Research Corporation.)

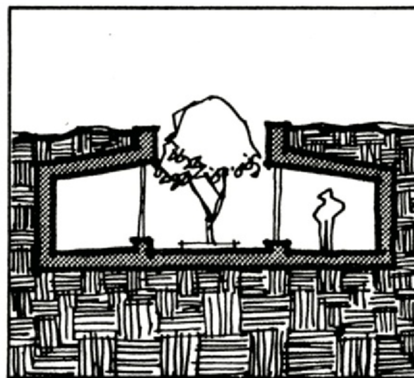
in Chapter 10 unless otherwise noted). (Fig. 5.10f)

a. All the strategies from priority V above also apply here.
b. Elevate the main living floor above the high humidity found near the ground.
c. Use plants sparsely. Minimize low trees, shrubbery, and ground covers to enable air to circulate through the site to remove moisture. Use only trees that have a high canopy. (Chapter 11)
d. Avoid basements in hot and very humid climates.

VII. Use thermal mass to reduce day-to-night temperature swings in the summer (covered in Chapter 10 unless noted otherwise). (Fig. 5.10g)

a. Cool the thermal mass with night ventilation, a strategy known as night-flush cooling.
b. Use massive construction materials since they have a high heat capacity. Use materials such as brick, concrete, stone, and adobe. (Chapter 15)
c. Place insulation on the outside of the thermal mass. (Chapter 15)
d. If massive materials are also to be used on the outside, sandwich the insulation between the inside and outside mass walls. (Chapter 15)
e. Use earth sheltering, with the earth or rock in direct contact with the uninsulated walls. (Chapters 10 and 15)
f. Keep daytime hot air out of the building by closing all openings.
g. Open the building at night to allow cool air to enter. Use the strategies of natural ventilation, listed above in priority V, to maximize the night cooling of the thermal mass.
h. Use water as a thermal mass because of its very high heat capacity. Use containers that maximize heat transfer into and out of the water. (Chapter 7)
i. Use radiant or evaporative cooling for additional temperature drop in the thermal mass at night.
j. Use mechanical equipment at night when it is most efficient





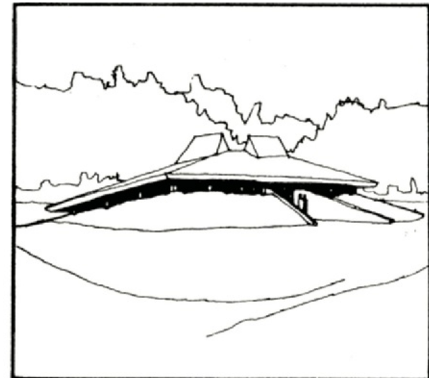
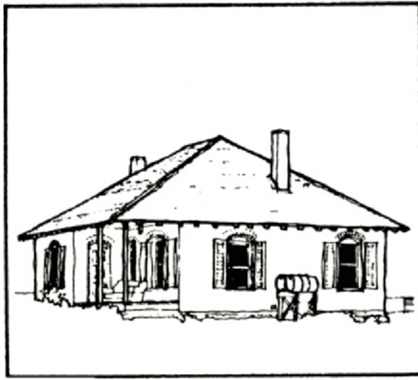
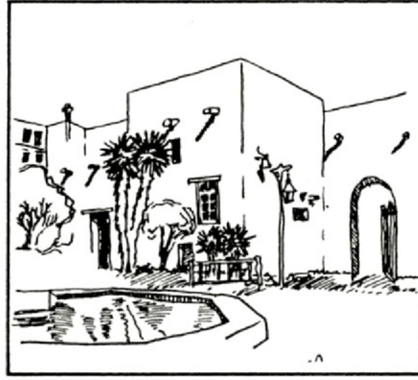


Figure 5.10g Use thermal mass to reduce the impact of high temperatures. Use the thermal mass of the earth. Use berms or sloping sites for earth-sheltered buildings. (Drawings from *Regional Guidelines for Building Passive Energy Conserving Homes* by the AIA Research Corporation.)





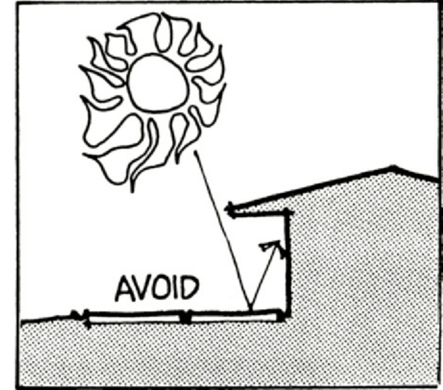


Figure 5.10h Use compact, well-insulated, and white-painted buildings. Use attached housing units to minimize the exposed wall area. Have buildings shade each other. Avoid reflecting sun into windows. (Drawings from *Regional Guidelines for Building Passive Energy Conserving Homes* by the AIA Research Corporation.)

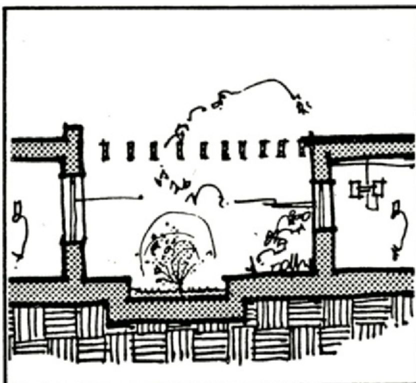
to create a heat sink. By cooling the building at night, the cool thermal mass can soak up heat the next day. (Chapter 16)

VIII. Keep hot temperatures out during the summer (Fig. 5.10h).

a. Use compact designs to minimize the surface-area-to-volume ratio. (Chapter 15)
b. Build attached houses to minimize the number of exposed walls. (Chapters 11 and 15)
c. Use vegetation and shade structures to maintain cool ambient air around the building and to prevent reflecting sunlight into the windows. (Chapter 11)
d. Use earth sheltering in the form of underground or bermed structures. (Chapter 15)
e. Use plenty of insulation in the building envelope. (Chapter 15)
f. Use few and small windows to keep heat out. (Chapter 15)
g. Use exterior window shutters. In hot climates use double glazing, and in very hot climates also use movable insulation over windows during the day when a space is unoccupied (e.g., a bedroom). (Chapter 15)
h. Isolate sources of heat in a separate room, wing, or building (e.g., kitchen). (Chapter 15)
i. Zone building so that certain spaces are cooled only while occupied. (Chapter 16)
j. Use light-colored roofs and walls to reflect the sun's heat (Chapter 9).

IX. Use evaporative cooling in the summer (covered in Chapter 10 unless otherwise noted) (Fig. 5.10i).

a. Locate pools or fountains in the building, in a courtyard, or in the path of incoming winds.
b. Use transpiration by plants to cool the air both indoors and outdoors.
c. Spray water on roof, walls, and patios to cool these surfaces.
d. Pass incoming air through a curtain of water or a wet fabric.
e. Use a roof pond or another indirect evaporative cooling system.
f. Use an evaporative cooler. This simple and inexpensive mechanical device uses very little electrical energy.





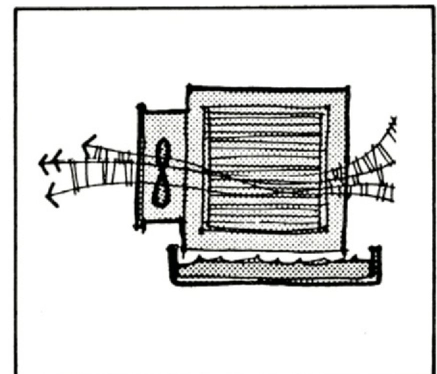
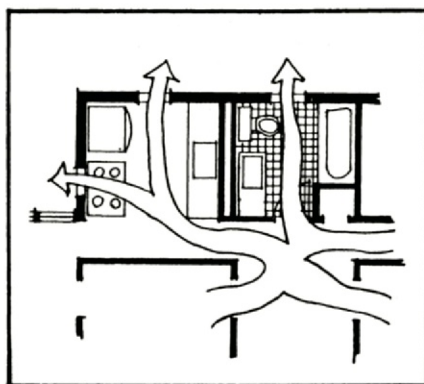


Figure 5.10i Use fountains, pools, and plants for evaporative cooling. Use courtyards to prevent cooled air from blowing away. Use energy-conserving evaporative coolers. (Drawings from *Regional Guidelines for Building Passive Energy Conserving Homes* by the AIA Research Corporation.)



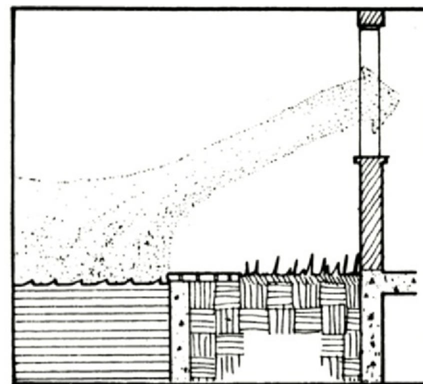


Figure 5.10j Use exhaust fans to remove excess moisture from kitchens, bathrooms, and laundry rooms. In humid climates, minimize indoor plants, and keep them out of direct sunlight to reduce transpiration. Avoid pools, fountains, and plants in the landscape. Minimize interior partitions, and provide many openings in the exterior walls. (Drawings from *Regional Guidelines for Building Passive Energy Conserving Homes* by the AIA Research Corporation.)

X. Avoid creating additional humidity during the summer (covered in Chapter 10) (Fig 5.10j).
   a. Do not use evaporative cooling strategies in humid climates.
   b. Use underground or drip rather than spray irrigation.
   c. Avoid pools and fountains.
   d. Keep the area around the building dry by providing the proper drainage of land. Channel runoff water from the roof and paved areas away from the site.
   e. Use permeable paving materials to prevent puddles on the surface.
   f. Minimize plants, especially indoors. Use plants that add little water to the air by transpiration. Such plants are usually native to dry climates. Use trees that have a high canopy.
   g. Shade plants and pools of water both indoors and out because the heat of the sun greatly increases the rate of transpiration and evaporation.
   h. Use exhaust fans in kitchens, bathrooms, laundry rooms, etc., to remove excess moisture.

XI. Open the building to the outdoors since temperatures are comfortable much of the year (covered in Chapter 10)(Fig. 5.10k).
   a. Create outdoor spaces with different orientations for use at different times of the day and year. For example, use outdoor spaces on the south side in the winter and on the north side in the summer.
   b. Create outdoor living areas that are sheltered from the hot summer sun and cool winter winds.
   c. Use noncompact building designs for maximum contact with the outdoors. Use an articulated building with many extensions or wings to create outdoor living spaces.
   d. Use large areas of operable windows, doors, and even movable walls to increase contact with the outdoors.
   e. Create pavilion-like buildings that have few interior partitions and minimal exterior walls.

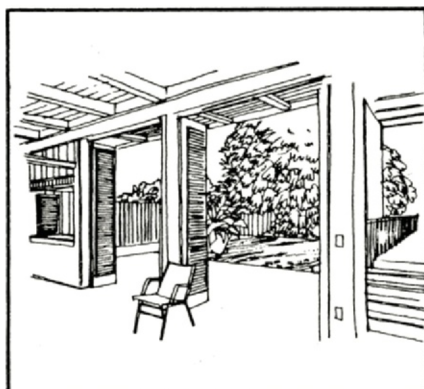
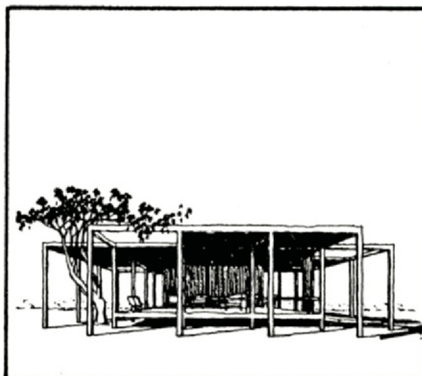
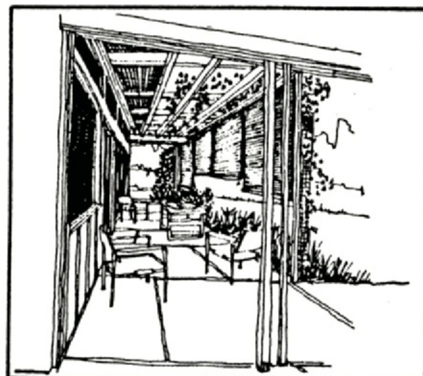




Figure 5.10k Use operable and movable wall panels. Create sheltered outdoor spaces with various orientations for use at different times of day and year. (Drawings from *Regional Guidelines for Building Passive Energy Conserving Homes* by the AIA Research Corporation.)

KEY IDEAS OF CHAPTER 5

1. Because of water vapor and clouds in hot and humid climates, daytime temperatures are lower and nighttime temperatures are higher. Thus, the diurnal temperature range is small.
2. Because of lack of water in the air, hot and dry climates have high daytime temperatures and low nighttime temperatures. Thus, the diurnal temperature range is large.
3. Because of such features as elevation, form of land, large bodies of water, soil types, vegetation, and man-made objects, the microclimate can be significantly different from the regional climate.
4. Typical wind directions and intensities are documented by wind roses.
5. The building bioclimatic chart is an excellent tool for understanding a climate in terms of temperatures and the coincident RH.
6. Sunshine charts indicate the amount of direct sunshine available for shading, solar heating, and daylighting for each climate region.
7. The degree-days chart is an excellent tool for determining the depth and severity (heating and cooling loads) of winter and summer.
8. Design priorities are given for each of the seventeen climate regions detailed in this chapter. Design strategies or techniques for addressing these priorities are given at the end of the chapter.

Acknowledgment

Much of the material in this chapter was taken from the book *Regional Guidelines for Building Passive Energy Conserving Homes* by the AIA Research Corporation.

Resources

Further Reading

(See the Bibliography in the back of the book for full citations.)

AIA Research Corporation. *Regional Guidelines for Building Passive Energy Conserving Homes*.

ASHRAE Handbook. Fundamentals. Compatative Climatic Data for the United States.

Fitch, J. M., with W. Bobenhausen. *American Building: The Environmental Forces That Shape It*.

Gronzik, W. T., et al. *Mechanical and Electrical Equipment for Buildings*, 11th ed.

National Oceanic and Atmospheric Administration (NOAA). *Climate Atlas of the United States.*

Olgyay, V. *Design with Climate: A Bioclimatic Approach to Architectural Regionalism*.

Ruffner, J. A., and F. E. Bair. *The Weather Almanac*.

Watson, D., and K. Labs. *Climatic Design: Energy-Efficient Building Principles and Practices*.

Web Resources—United States

Climate Atlas of the United States, published in 1968 and reprinted in 1983 by the National Oceanic and Atmospheric Administration (NOAA), National Climate Data Center (NCDC) (contains maps of the United States showing contour lines for various climate conditions) www.wrcc.dri.edu/climmaps

National Climatic Data Center of the United States www.ncdc.noaa.gov

National Resources Conservation Service (NRCS) www.wcc.nrcs.usda.gov www.wcc.nrcs.usda.gov/climate/prism.html

- Climate information by county
- Digital maps of precipitation
- Wind roses

USA Climate, created by Sustainable By Design www.susdesign.com/usaclimate

Web Resources—World

Canadian climate—National Climate Data and Information Archive (excellent source for climate of cities all over Canada) www.climate.weatheroffice.ec.gc.ca

World Climate—limited climate information for cities all over the world www.worldclimate.com

CHAPTER 6

SOLAR GEOMETRY

It is the mission of modern architecture to concern itself with the sun.

Le Corbusier, from a letter to Sert.

A building cannot be energy efficient if it is not solar responsive.

Orientation is the most valuable energy-saving strategy.

6.1 INTRODUCTION

People used to worship the sun as a god; they understood how much life depended on sunshine. However, with the rapid growth of science and technology, humankind came to believe that all problems could be solved by high technology and that it was no longer necessary to live in harmony with nature. An architectural example of this attitude is the construction of an all-glass building in the desert, which can be kept habitable only by means of huge energy-guzzling air-conditioning plants.

The looming crisis of global warming must persuade us to reconsider our relationships with nature and technology. There is a deepening conviction that progress will come mainly from technology that is in harmony with nature. The fast-growing interest in sustainable or green design illustrates this shift in attitude. In architecture, this point of view is represented by buildings that let the sun shine in during the winter and are shaded from the sun in the summer (see Fig. 6.1).

This approach to architecture requires that the designer have a good understanding of the natural world. Central to this understanding is the relationship of the sun to the earth. This chapter discusses solar radiation and solar geometry.

6.2 THE SUN

The sun is a huge fusion reactor in which light atoms are fused into heavier atoms, and in the process energy is released. This reaction can occur only in the interior of the sun, where the necessary temperature of 25,000,000°F (14,000,000°C) exists. The solar radiation reaching earth, however, is emitted from the sun's surface, which is much cooler (Fig. 6.2a). Solar radiation is, therefore, the kind of radiation that a body having a temperature of about 10,000°F (5,500°C) emits. The amount and composition of solar radiation reaching the outer edge of the earth's atmosphere are quite unvarying and are called the solar constant. The amount and composition of the radiation reaching the earth's surface, however, vary widely with sun angles, elevation, and the composition of the atmosphere (Fig. 6.2b).



Figure 6.1 Part of the year the sun is our friend, and part of the year it is our enemy. (Drawing by Le Corbusier from Le *Corbusier: Oevre Complete, 1938–1944*, Vol. 4, by W. Boesiger, 7th ed. *Verlag fuer Architektur* Artemis © 1977.) With kind permission from Springer Science and Business Media.

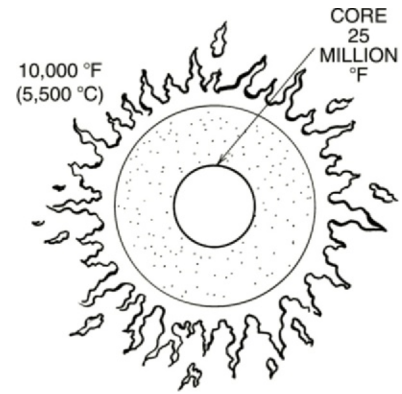


Figure 6.2a The surface temperature of the sun determines the type of radiation emitted.

6.3 ELLIPTICAL ORBIT

The orbit of the earth is not a circle but an ellipse, so that the distance between the earth and the sun varies as the earth revolves around the sun (Fig. 6.3). The distance varies about 3.3 percent, and this results in a small annual variation in the intensity of solar radiation.

Does this explain why it is cooler in January than in July? No, because we are actually closer to the sun in January than July. In fact, this variation in distance from the sun slightly reduces the severity of winters and summers in the Northern Hemisphere. What then is the cause of the seasons?

Since the sun is very far away and since it lies in the plane of the earth's orbit, solar radiation striking the earth is always parallel to this plane (Fig. 6.3). While the earth revolves around the sun, it also spins around its own north–south axis. Because this axis is not perpendicular to the orbital plane but is tilted 23.5° off the normal to this plane, and because the orientation in space of this axis of rotation remains fixed as the earth revolves around the sun, the angle at which the sun's rays hit the earth continuously changes throughout the year. This tilt of 23.5° is the cause of the seasons and has major implications for solar design.

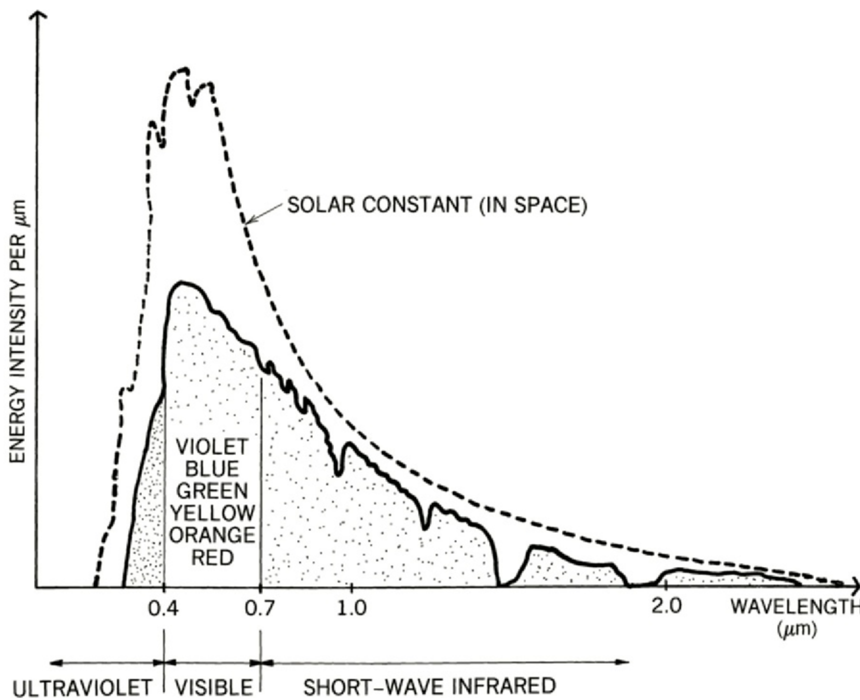


Figure 6.2b The solar spectrum at the earth's surface consists of about 47 percent visible, 48 percent short-wave infrared, and about 5 percent ultraviolet radiation.

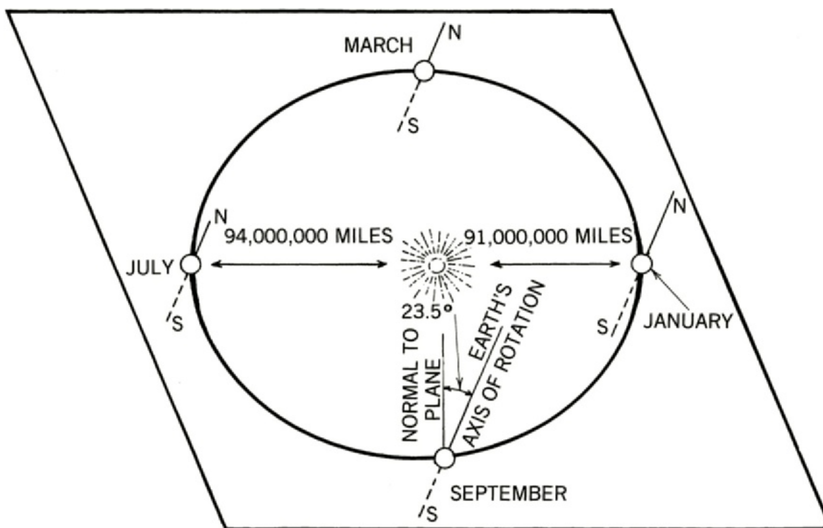


Figure 6.3 The earth's axis of rotation is tilted to the plane of the elliptical orbit. The distance to the sun is 3,000,000 mi (4,800,000 km) closer in January than in July.

6.4 TILT OF THE EARTH'S AXIS

Because the tilt of the earth's axis is fixed, the Northern Hemisphere faces the sun in June and the Southern Hemisphere faces the sun in December (Fig. 6.4a). The extreme conditions occur on June 21, when the North Pole is pointing most nearly toward the sun, and on December 21, when the North Pole is pointing farthest away from the sun.

Notice that on June 21, the sun's rays are perpendicular to the earth's surface along the Tropic of Cancer, which is, not by coincidence, at latitude 23.5° N (Fig. 6.4b). No part of the earth north of the Tropic of Cancer ever has the sun directly overhead. It is also the longest day in the Northern Hemisphere and is called the summer solstice. Furthermore, on that day, all of the earth north of the Arctic Circle will have twenty-four hours of sunlight.

Six months later, on December 21, at the opposite end of the earth's

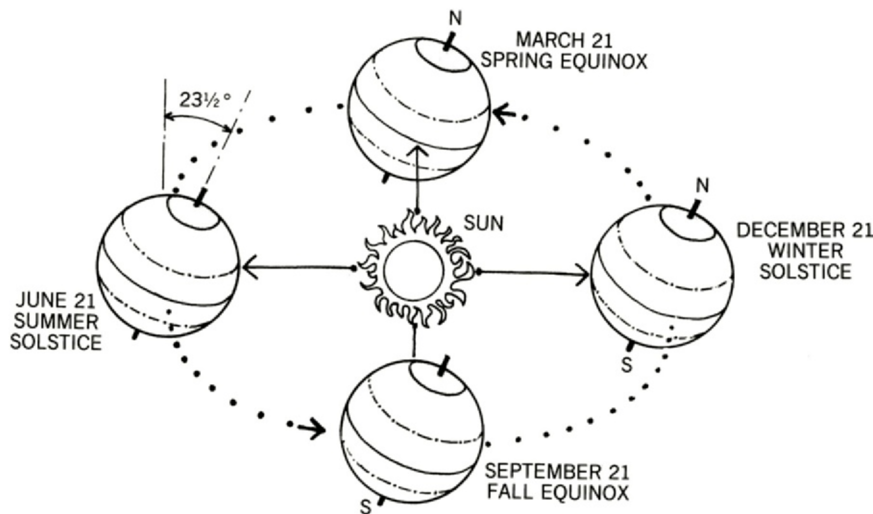


Figure 6.4a The seasons are a consequence of the tilt of the earth's axis of rotation. (From *Solar Dwelling Design Concepts* by AIA Research Corporation, U.S. Dept. Housing and Urban Development, 1976. HUD-PDR-154(4).)

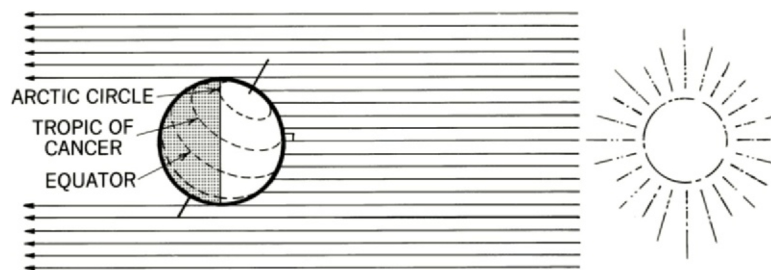


Figure 6.4b During the summer solstice (June 21), the sun is directly overhead on the Tropic of Cancer, which is 23.5° N latitude.

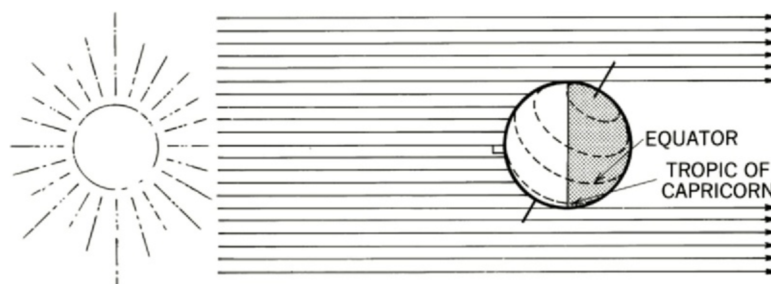


Figure 6.4c During the winter solstice (December 21), the sun is directly overhead on the Tropic of Capricorn, which is 23.5° S latitude.

orbit around the sun, the North Pole points so far away from the sun that now all of the earth above the Arctic Circle experiences twenty-four hours of darkness (Fig. 6.4c). In the Northern Hemisphere, it is the day with the longest night and is known as the winter solstice. On this day, the sun is perpendicular to the Southern Hemisphere along the Tropic of Capricorn, which, of course, is at latitude 23.5° S. Meanwhile, the sun's rays that do fall on the Northern Hemisphere do so at much lower sun angles (altitude angles) than those striking the Southern Hemisphere.

Halfway between the longest and shortest days of the year is the day of equal nighttime and daytime hours. This situation occurs twice a year, on March 21 and September 21, called the spring and fall equinox (Fig. 6.4a). On these days, the sun is directly overhead on the equator.

6.5 CONSEQUENCES OF THE ALTITUDE ANGLE

The vertical angle at which the sun's rays strike the earth is called the altitude angle and is a function of the latitude, time of year, and time of day. In Figure 6.5a we see how the altitude angle is derived from these three factors. The simplest situation occurs at 12 noon on the equinox, when the sun's rays are perpendicular to the earth at the equator (Fig. 6.5a). To find the altitude angle of the sun at any latitude, draw the ground plane tangent to the earth at that latitude. By simple geometric principles, it can be shown that the altitude angle is equal to 90° minus the latitude. There are two important consequences of this altitude angle on climate and the seasons.

The first effect of the altitude angle is illustrated by Figure 6.5b, which indicates that at low angles the sun's rays pass through more of the atmosphere. Consequently, the radiation reaching the surface will be weaker and more modified in composition. The extreme case occurs at sunset, when the radiation is red and weak enough to be looked at. This is because of the selective absorption, reflection, and refraction of solar radiation in the atmosphere.

The second effect of the altitude angle is illustrated in the diagram of the cosine law (Fig. 6.5c). This law says that a given beam of sunlight will illuminate a larger area as the sun gets lower in the sky. As the given sunbeam is spread over larger areas, the

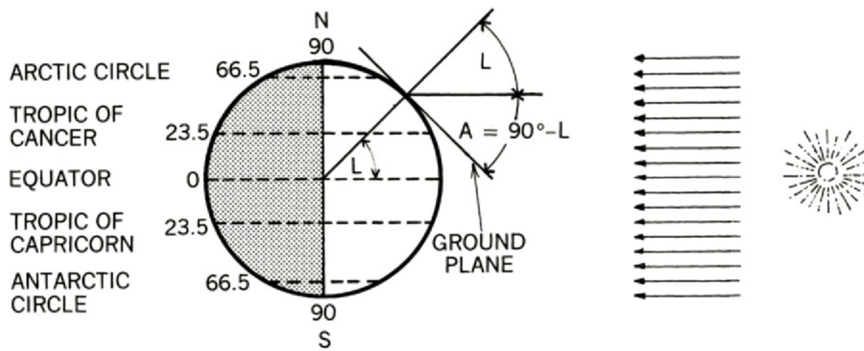


Figure 6.5a On the equinox, the sun's altitude (A) at solar noon at any place on earth is equal to 90° minus the latitude (L).

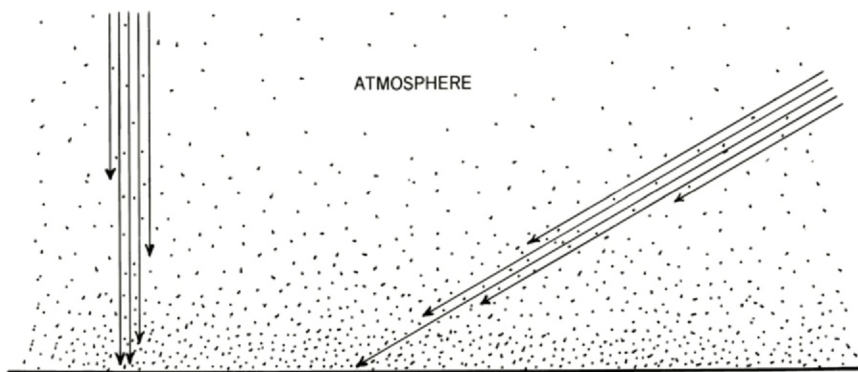


Figure 6.5b The altitude angle determines how much of the solar radiation will be absorbed by the atmosphere.

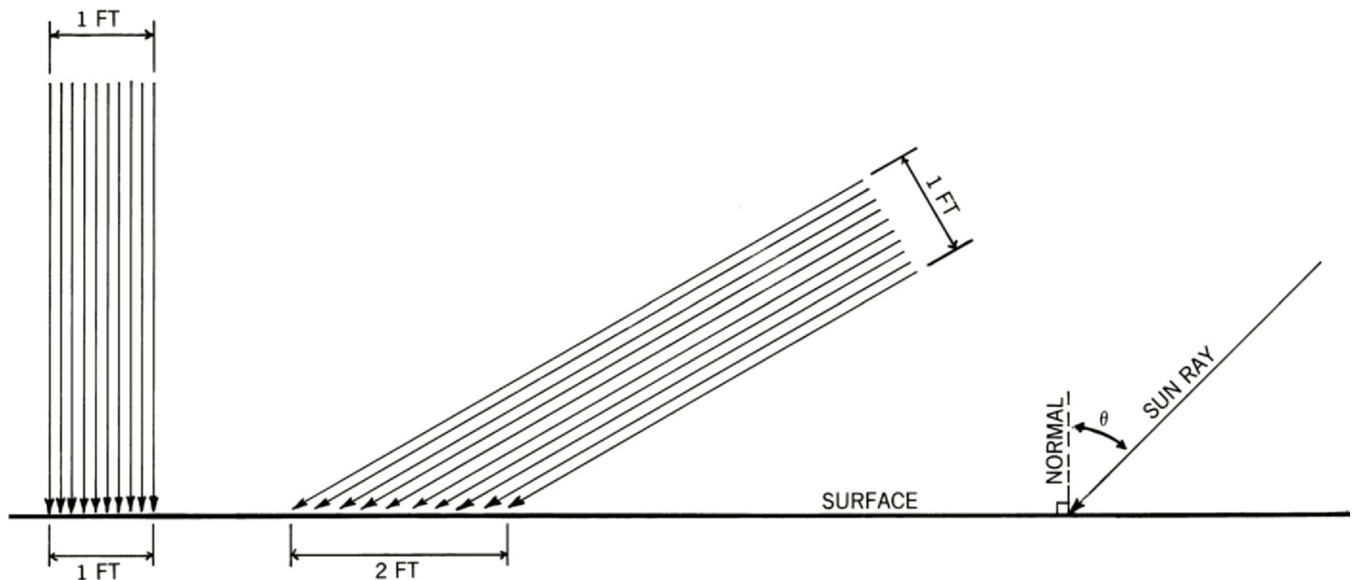


Figure 6.5c A vertical sunbeam with a cross section of 1 ft^2 (1 m^2) will heat 1 ft^2 (1 m^2) of land. At a certain low-altitude angle, however, that same 1 ft^2 (1 m^2) sunbeam will heat 2 ft^2 (2 m^2) of land. Consequently, each square foot (m^2) of land receives only half the solar heating. Thus, as the altitude angle decreases, so does the heating of the land. This phenomenon is called the cosine law, because the radiation received by a surface is a function of the cosine of angle θ measured from the normal to the surface.

sunlight on each square unit of land naturally gets weaker. The amount of sunlight that a surface receives changes with the cosine of the angle between the sun's rays and the normal to the surface.

6.6 WINTER

Now we can understand what causes winter. The temperature of the air, as well as that of the land, is mainly a result of the amount of solar radiation absorbed by the land. The air is mainly heated or cooled by its contact with the earth. The reasons for less radiation falling on the ground in the winter follow.

Most important is the fact that there are far fewer hours of daylight in the winter. The exact number is a function of latitude (see Table 5.6). As was mentioned earlier, there is no sunlight above the Arctic Circle on December 21, and at 40° latitude, for example, there are almost six fewer hours of daylight on December 21 than on June 21.

The second reason for reduced heating of the earth is the cosine law. On December 21, the solar radiation falling on a square foot (square meter) of land is significantly less than that on June 21.

Lastly, the lower sun angles increase the amount of atmosphere the sun must pass through and, therefore, there is again less radiation reaching each square foot (square meter) of land.

6.7 THE SUN REVOLVES AROUND THE EARTH!

Despite threats of torture and death, Galileo and Copernicus spoke up and convinced the world that the earth revolves around the sun. Nevertheless, I would like to suggest, for nonreligious reasons, that we again assume that the sun revolves around the earth or at least that the sun revolves around the building in question. For the moment, this assumption makes it infinitely more convenient to understand sun angles. To make things even more convenient, let us also assume a sky dome (Fig. 6.11a), where a large clear plastic hemisphere is placed over the building site in question.

6.8 THE SKY DOME

In Figure 6.8a we see an imaginary sky dome placed over the building site. We are interested only in the sunrays that penetrate the sky dome on their way to the building at the center. The points where these sunrays penetrate the sky dome every hour are marked. When all the points for one day are connected, we get a line on the sky dome called the sun path for that day. Figure 6.8a shows the highest sun path of the year (summer solstice), the lowest sun path (winter solstice), and the middle sun paths (equinoxes). Note that the sun enters the sky dome only between the sun paths of the summer and winter solstices. Since the solar radiation is quite weak in the early and late hours of the day, the part of the sky dome through which the most powerful sunrays enter is called the solar window. Figure 6.8b shows the conventional solar window, which is assumed to begin at 9 A.M. and end at 3 P.M. Ideally, no trees, buildings, or other obstacles should block the sunrays entering through the solar window during those months when solar energy is desired. Space heating requires solar access only during the winter months (the lower portion of the solar window), while domestic hot-water heating and photovoltaics (PV) require solar access for the whole year (whole solar window).

An east elevation of the sky dome is illustrated in Figure 6.8c. The sun paths for the summer solstice (June 21), equinoxes (March 21 and September 21), and winter solstice (December 21) are shown in edge view. The afternoon part of the sun path is directly behind the morning part. The mark for 3 P.M. is, therefore, directly behind the 9 A.M. mark labeled in the diagram.

The sun's motion is completely symmetrical about a north–south axis. Notice in the diagram that the sun moves 23.5° on either side of the equinoxes because of the tilt of the earth's axis of rotation. The total

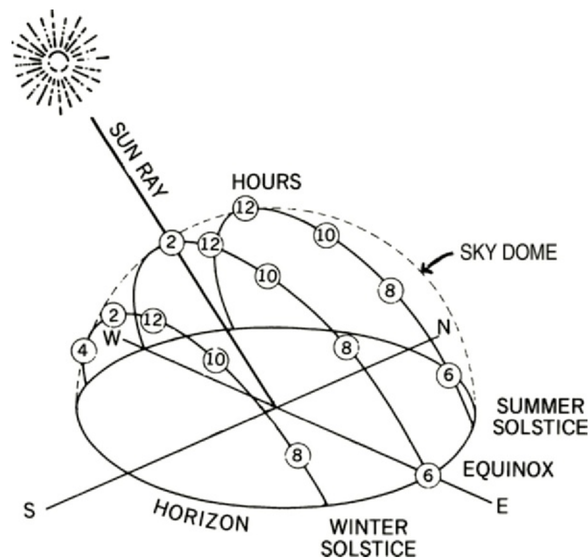


Figure 6.8a The sky dome and the three sun paths of June 21, September/March 21, and December 21 are shown. (From *Architectural Graphic Standards*, by Ramsey/Sleeper, 8th ed. John R. Hoke, ed. copyright John Wiley, 1988.)

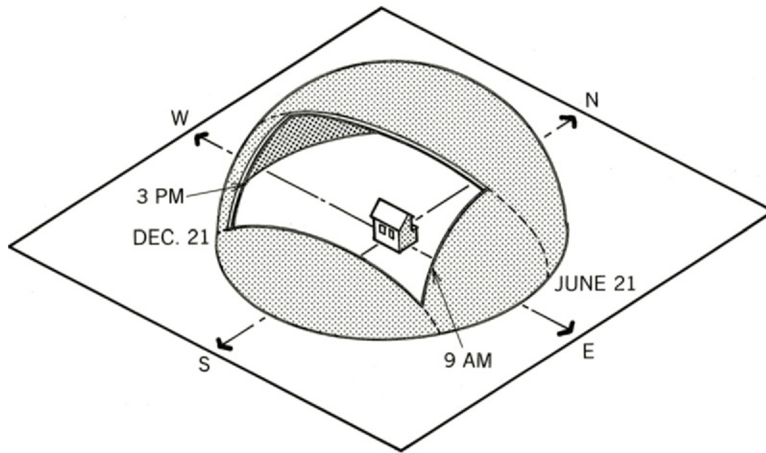


Figure 6.8b The part of the sky dome between the December 21 and June 21 sun paths is called the solar window. Most radiation in the winter is received between 9 A.M. and 3 P.M.

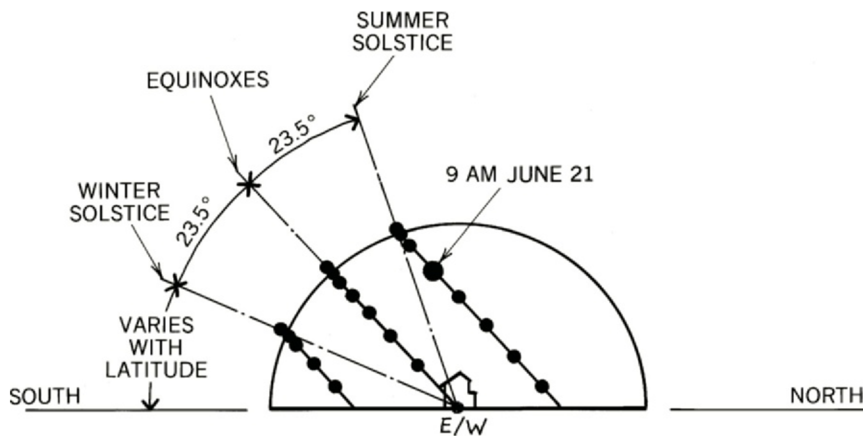


Figure 6.8c An east elevation of the sky dome is shown. The east–west axis is the point at the center of the sky dome. It is also where the sun rises and sets on the equinoxes. (From *Solar Dwelling Design Concepts*, by AIA Research Corporation. U.S. Dept. Housing and Urban Development, 1976. HUD-PDR-154(4).)

vertical travel between winter and summer is, therefore, 47°. The actual altitude angles, however, depend on the latitude.

6.9 DETERMINING ALTITUDE AND AZIMUTH ANGLES

By far the easiest way to work with the compound angle of sunrays is to use component angles. The most useful components are the altitude angle, which is measured in a vertical plane, and the azimuth angle, which is measured in a horizontal plane.

In Figure 6.9a we see a sunray enter the sky dome at 2 P.M. on the equinox. The horizontal projection of this sunray lies in the ground plane. The vertical angle from this projection

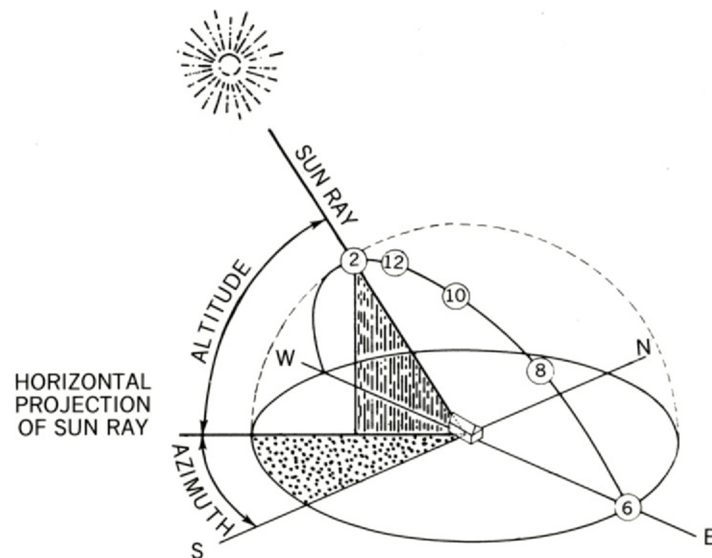


Figure 6.9a Definition of altitude and azimuth angles. (From *Architectural Graphic Standards*, Ramsey/Sleeper 8th ed. John R. Hoke, ed. copyright John Wiley, 1988).

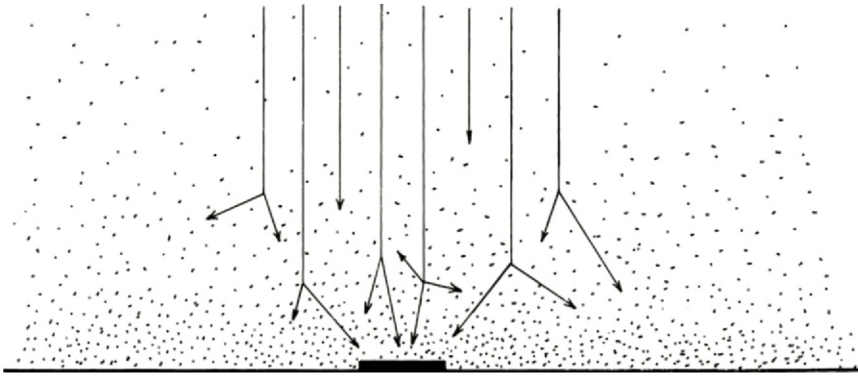


Figure 6.9b Diffuse radiation.

to the sunray is called the altitude. It tells us how high the sun is in the sky. The horizontal angle, which is measured from south on a north–south line, is called the azimuth.

It is important to understand that the above discussions on sun angles refer only to direct radiation. Water and dust particles scatter the solar radiation (Fig. 6.9b), so that on cloudy, humid, or dusty days the diffuse radiation becomes the dominant form of solar energy.

6.10 SOLAR TIME

At 12 noon solar time, the sun is always due south. However, the sun is not due south at 12 noon clock time because solar time varies from clock time for three reasons. The first is the common use of daylight savings time. The second is the deviation in longitude of the building site from the standard longitude of the time zone. The third reason is a consequence of the fact that the earth's speed in its orbit around the sun changes during the year. The amount of correction, therefore, depends on the time of year. Changing solar time to clock time or vice versa is quite complicated, and fortunately, the conversion is almost never necessary since our goal is simply to collect the sunrays when it is too cold and to reject the sunrays when it is too hot, or our goal is to collect sunrays all day long for daylighting, solar hot water, and solar electricity. Therefore, the conversion is not explained in this book, and all references to time are in solar time. The author can think of only one situation where knowing the clock time of certain sun angles is important in architecture. The situation, very rare today, is designing a temple to the sun where a beam of sunlight hits the altar at a particular clock time in order to evoke some magic.

6.11 HORIZONTAL SUN-PATH DIAGRAMS

Although altitude and azimuth angles can be readily obtained from tables, it is more informative to obtain the information from sun-path diagrams. In Figure 6.11a we again see the sky dome, but this time it has a grid of altitude and azimuth lines drawn on it, just as a globe of the earth has latitude and longitude lines. Just as there are maps of the world that are usually either cylindrical or polar projections, there are vertical or horizontal projections of the sky dome (Fig. 6.11b). Notice how the grids project on the horizontal and vertical planes.

The sky dome shown in Figure 6.11a has an azimuth grid, an altitude grid, and the sun paths for each month of the year for 32° N latitude. When the sun paths are plotted on a horizontal projection of the sky dome, we get a sun-path diagram such as the one shown in Figure 6.11c. In these diagrams, the sun path of day 21 of each month is labeled by a Roman numeral (e.g., XII represents December). The hours of the day are labeled along the sun path of June (VI). The concentric rings describe the altitude, and the radial lines define azimuth. The sun-path diagram for 36° N latitude is shown in Fig. 6.11c. Additional sun-path diagrams, at 4° latitude intervals, are found in Appendix A.

Example: Find the altitude and azimuth of the sun in Memphis, Tennessee, on February 21 at 9 A.M., and then draw the sunbeams representing the sun at this time on a plan and section.

Step 1. From a map of the United States, find the latitude of Memphis (see Fig. 5.6d). Since it is at about 35° latitude, use the sun-path diagram for 36° N latitude (found in Appendix A and Fig. 6.11c).

Step 2. On this sun-path diagram, find the intersection of the sun path for February 21 (curve II) and the 9 A.M. line. This point represents the location where the sunray penetrates the sky dome. The intersection is shown as a heavy dot in Fig. 6.11c.

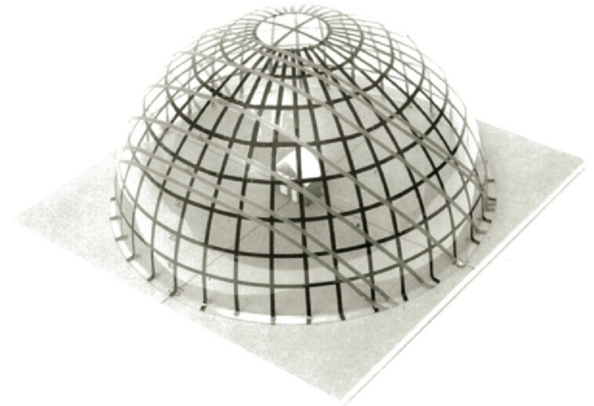
Step 3. From the concentric circles, the altitude is found to be about 27°.

Step 4. From the radial lines, the azimuth is found to be about 51° east of south.

Step 5. On a plan of the building, use the azimuth angle to draw the left- and rightmost sunrays through the east and south windows (Fig. 6.11d).

Step 6. On a section through the east window, use the altitude angle to draw the top- and bottommost sunrays (Fig. 6.11d).

Step 7. Shade in the area between the extreme sunrays at each window to create the sunbeams representing both the direction and magnitude of the sunbeams entering these windows (Fig. 6.11d).



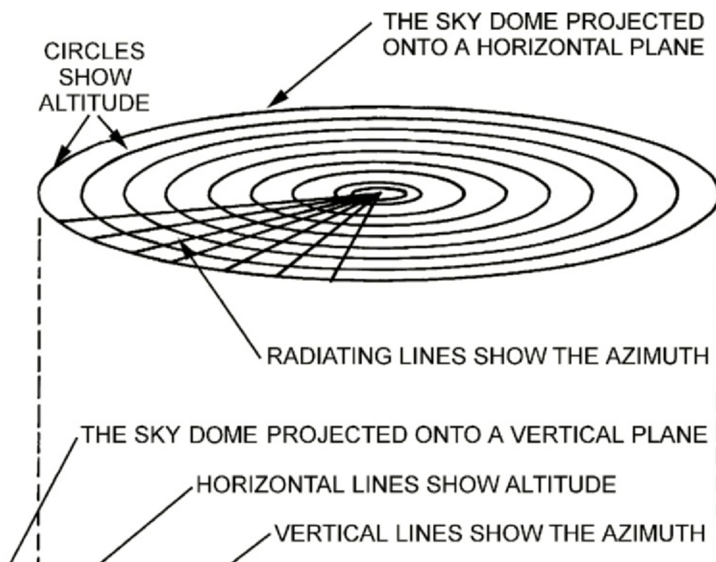


Figure 6.11a A model of the sky dome. The sun paths for the twenty-first day of each month are shown. Only seven paths are needed for twelve months because of symmetry (i.e., May 21 has the same path as July 21).

Figure 6.11b Derivation of the horizontal and vertical sun-path diagrams.

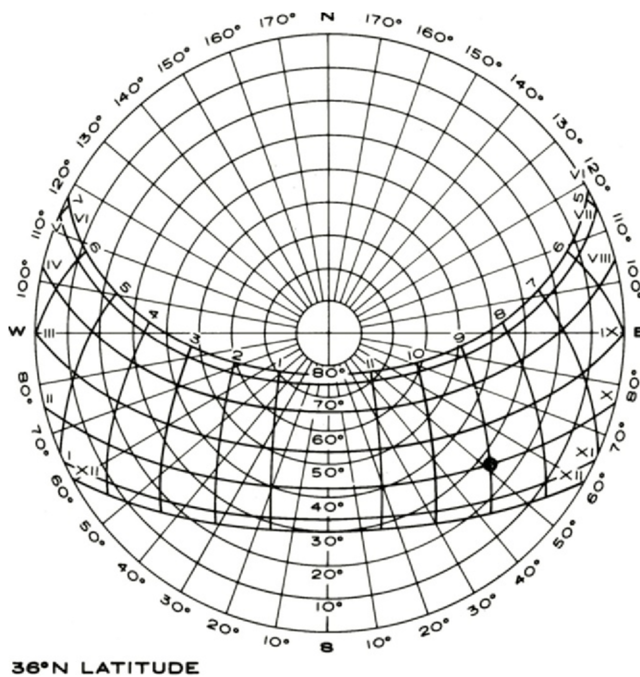


Figure 6.11c Horizontal sun-path diagram. A complete set of these diagrams is found in Appendix A. (From *Architectural Graphic Standards*. Ramsey/Sleeper 8th ed. John R. Hoke, ed. copyright John Wiley, 1988.)

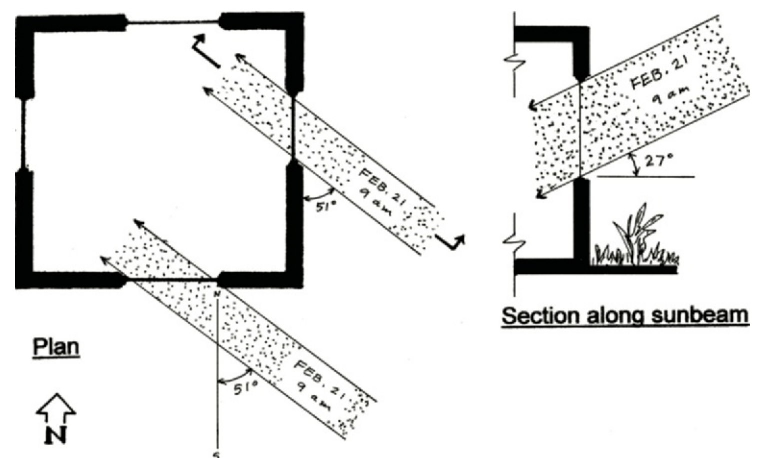


Figure 6.11d The azimuth angle measured from a north–south line is used to draw the sunbeam in plan. The altitude angle is used to draw the sunbeam in section. To prevent graphical distortion, the section is cut along the sunbeam, as can be seen from the section marks on the east window in plan.

6.12 VERTICAL SUN-PATH DIAGRAMS

Figure 6.11b also shows how a vertical projection of the sky dome is developed. Notice that the apex point of the sky dome is projected as a line. Consequently, severe distortions occur at high altitudes. In Figure 6.12a, we see a vertical sun-path diagram for 36° N latitude.

Altitude and azimuth angles are found in a manner similar to that used in the horizontal sun-path diagrams. Appendix B has vertical sun-path diagrams at 4° intervals.

Example: Find the altitude and azimuth of a sunray in Albuquerque, New Mexico, on March 21 at 3 P.M., and then draw the sunbeams representing the sun at this time on a plan and section.

Step 1. From Appendix B, choose the sun-path diagram that is within 2° of the place in question. Since Albuquerque is at 35° N latitude, use the sun path for 36° N.

Step 2. Find the intersection of the curves for March 21 and 3 P.M. (see the circle in Fig. 6.12a).

Step 3. From the horizontal scale, the azimuth is found to be about 59° west of south.

Step 4. From the vertical scale, the altitude is found to be about 34° above the horizontal.

Step 5. On a plan of the building, use the azimuth angle to draw the left- and rightmost sunrays through the west and south windows (Fig. 6.12b).

Step 6. On a section along the sunray through the west window, use the altitude angle to draw the bottom- and topmost sunray (Fig. 6.12b).

Step 7. Shade in the area between the extreme sunrays at each window to create the sunbeams (Fig. 6.12b).

Besides being a source of sun-angle data, all sun-path diagrams are very helpful in creating a mental model of the sun's motion across the sky. The diagrams can also be used for visualizing and documenting the solar window and any obstacles that might be blocking it. The finely shaded area of Figure 6.12c is the winter solar window from 9 A.M. to 3 P.M. through March 21.

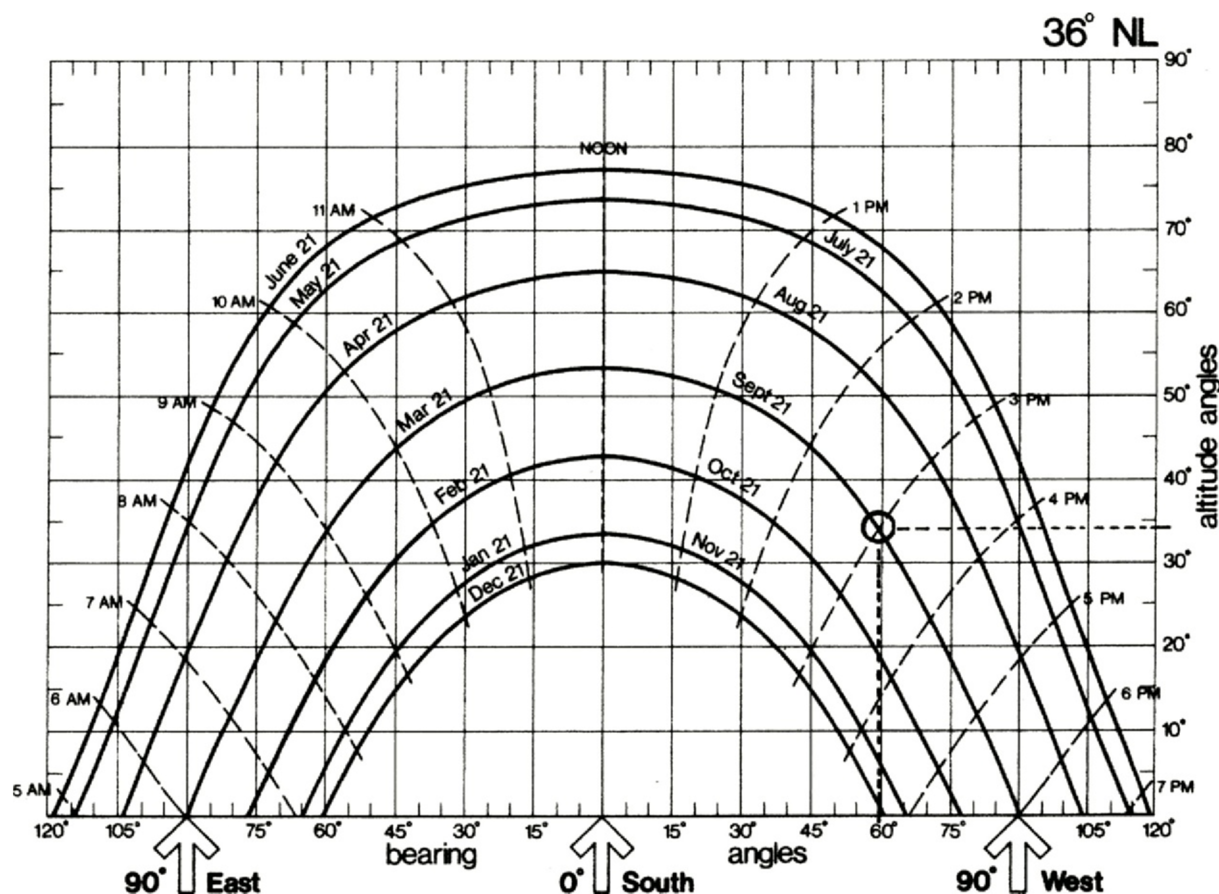


Figure 6.12a Vertical sun-path diagram. A complete set of these diagrams is found in Appendix B. (Reprinted from *The Passive Solar Energy Book*, copyright E. Mazria, 1979, by permission.)

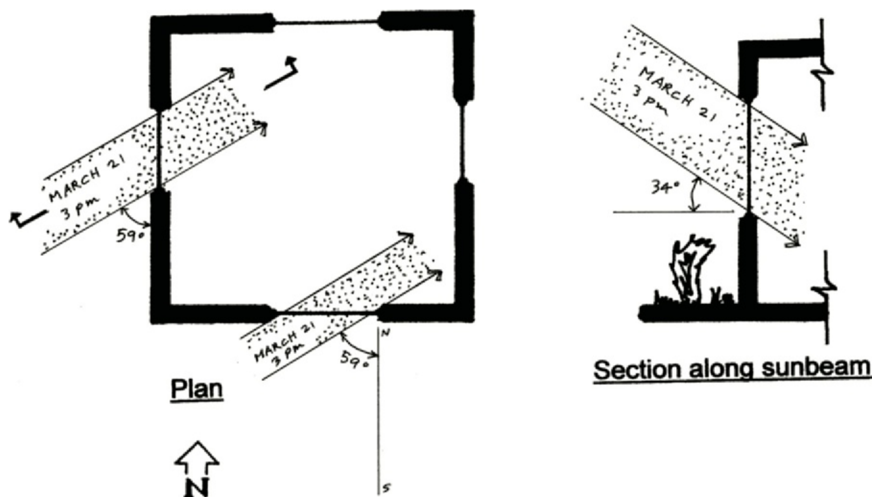


Figure 6.12b Azimuth angles are used to draw sunbeams in plan, and altitude angles are used in section. To prevent graphical distortion, the section is cut along the sunbeam, as can be seen on the west window in plan.

The roughly shaded area along the bottom represents the silhouette of trees and buildings surrounding a particular site. Notice that one building and one tree are partially blocking the solar window during the critical winter months. The easiest and quickest way to generate such a horizon profile is to use the site evaluation tools described in Section 6.16.

Although sun-path diagrams are invaluable for understanding solar geometry, sometimes it is easier to get the altitude and azimuth angles from a table. Thus, Appendix C provides a table of altitude and azimuth angles for every 4° of latitude from the equator to the poles.

Figure 6.12c The winter solar window and silhouette of surrounding objects are shown on this vertical sun-path diagram. The silhouette of a specific location was hand-drawn by means of a site evaluation tool described in Section 6.16. (Sun-path diagram from *The Passive Solar Energy Book*, copyright E. Mazria, 1979, reprinted by permission.)

6.13 DRAWING SUNBEAMS

The ability to draw sunbeams accurately is extremely important, because only correctly drawn sunbeams can prove that a particular solar responsive design actually works. An accurate representation of sunbeams both lets the designer know if his or her solar access and shading design works as intended and is the best way to show others the logic and validity of the solar responsive design. Many faulty solar responsive designs get built because the sunbeams were drawn incorrectly and therefore failed to raise a red flag.

Drawing sunbeams accurately is more difficult than most people believe, and the author is not aware of any computer program that can generate them. The reason for this inability will become clear as the method is explained below. The sections shown in Figures 6.11d and 6.12b illustrate the basic concept of drawing sunbeams in plan and the special section cut along the sunbeam. However,

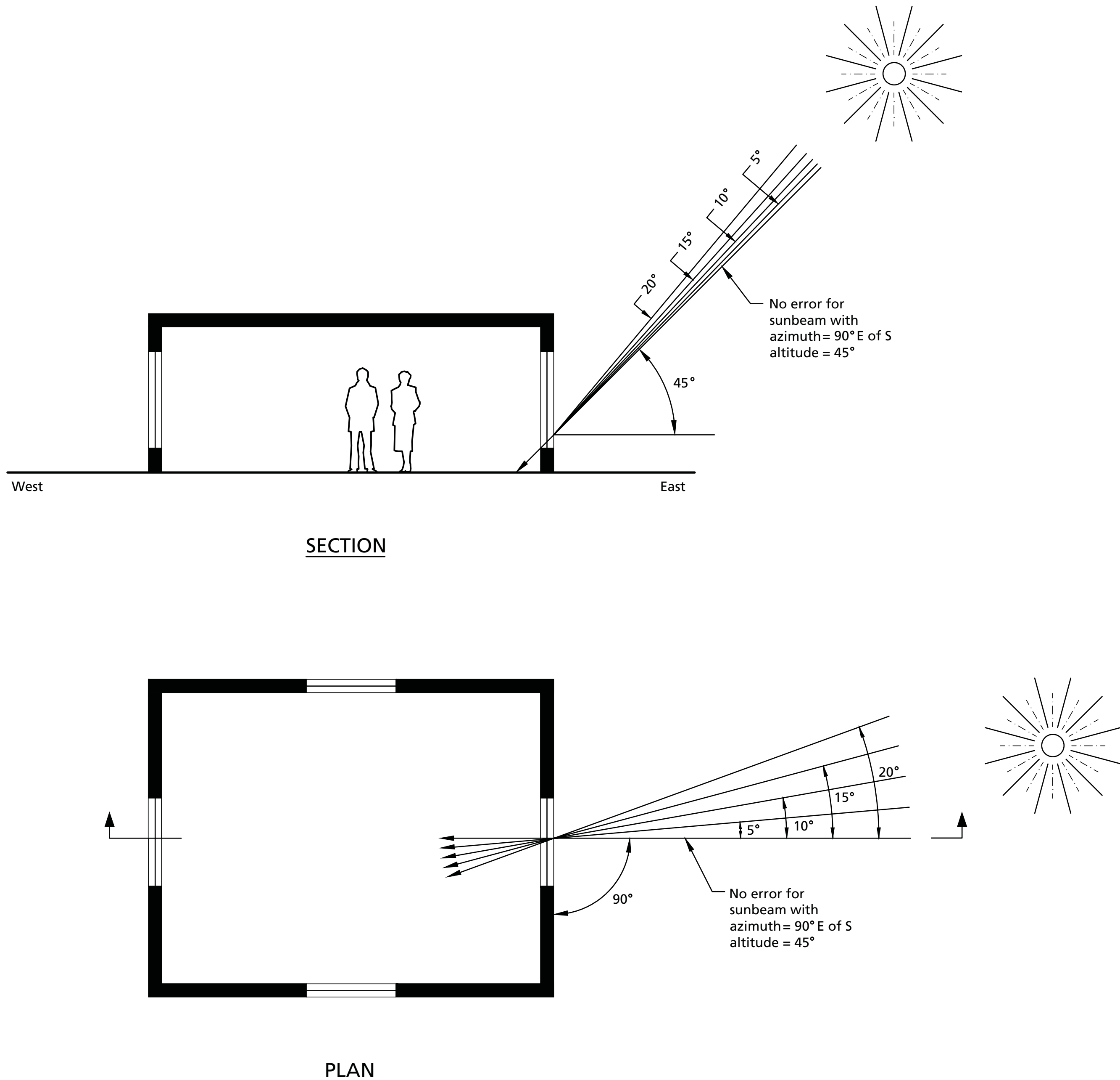


Figure 6.13a This figure illustrates the distortions that result when a sunbeam is out of the plane of the section. Of the five sunrays shown in the plan, only one is in the plane of the section. Thus, only one sunbeam can be drawn accurately in this section. However, if the sunbeam is less than 10° out of the section, the distortion is insignificant, and if it is less than 20° out of the section, it can still be drawn without creating a significant error.

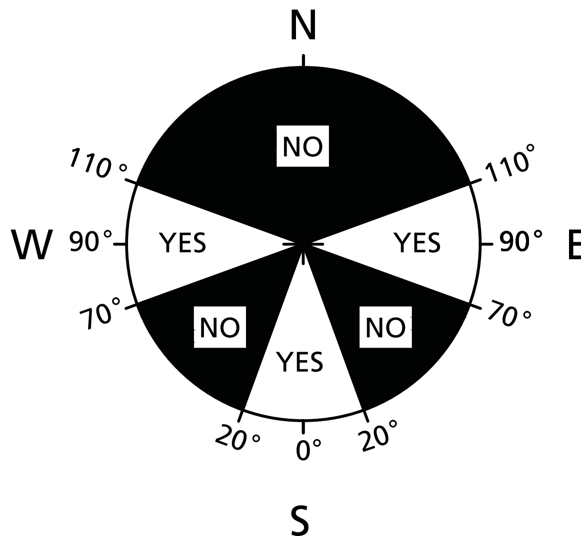


Figure 6.13b The key plan shown helps determine which sunbeams should be shown in standard sections. It also helps in visualizing the direction of each sunbeam, and it acts as a north arrow. This particular key plan is only appropriate for the Northern Hemisphere temperate zone.

drawing sunbeams becomes much more difficult when shading devices are present and becomes an art when standard sections are used instead of the special sections cut along the sunbeams. Except for a few special cases, sunbeams will not be in the plane of the normal building sections, and the further they are out of a section, the greater the distortion created. Because the building shown in Figure 6.13a is aligned with the compass, one of its normal sections runs east–west. Except for the sunbeam (sunray) that comes from due east (i.e., 90° E of S) all other sunbeams (sunrays) from northeast and southeast will look distorted when projected into this section. Fortunately, sunbeams up to 20° out of the section (see plan of Fig. 6.13a) can be shown in section without excessive distortion. Note that the distortion is a nonlinear function of how far the sunbeam is out of the section (i.e., there is little distortion at first). Table 6.13 expresses the amount of distortion in words, and the key plan in Figure 6.13b shows graphically which sunbeams can be safely shown in a standard section and which cannot. A copy of this key plan should be used as a guide when drawing sunbeams. Use the following guidelines for drawing accurate sunbeams.

Table 6.13 Out-of-Plane Distortions of Sunbeams

Degrees That Sunbeam Is Out of the Section (Horizontal Angle)	Resulting Distortion
0	no distortion
5	insignificant
10	minor
15	still acceptable
>20	not acceptable

Guidelines for Drawing Sunbeams

1. Show all sunbeams (sunrays) on a key plan, which also acts as the north arrow.
2. Show all sunbeams on plan, but only pencil them in lightly at this point. The sunbeams are as wide as defined by the sunrays on each side of the windows.
3. In section, show only those sunbeams that are within 20° of that section as seen on the key plan.
4. From the sections determine which sunbeams enter windows and which are blocked by an overhang. Then:
   a. If blocked, show sunbeams ending at the shading device in both section and plan view.
   b. If *not* blocked, show the sunbeams entering windows in both section and plan view.
5. For those sunbeams that cannot be shown in section because they are more than 20° out of those sections, do the following:
   a. If there are no shading devices, show the sunbeams entering the windows in plan view only, because they cannot be shown accurately in the section.
   b. If there are shading devices, a special section must be cut through the window aligned with the sunbeam (i.e., same azimuth) to determine if the sunbeams will enter the window.
6. Darken the sunrays entering on each side of the window in plan and section to determine the width and height of the sunbeam, and then color in the sunbeam. Use different colors to differentiate between sunbeams of varying dates and times when shown on the same plan and section (see Colorplate 36).

   Example: Draw the sunbeams for the times shown on the plan and sections of the building presented in Figure 6.13c. The building is located at 36° N latitude and aligned with the compass as shown on the key plan.

   Step 1. Find the altitude and azimuth angles for each sunbeam for 36° from Appendix C.

   Step 2. Draw each sunbeam (sunray) for the times shown on the key plan by using the azimuth angle. Label each sunbeam by its date and time.

   Step 3. Lightly pencil in the sunbeams on the plan by drawing the sunrays on each side of every relevant window.

   Step 4. From the key plan determine which sunbeams to show in section. Draw only those in the "yes" zones (i.e., within 20° of the plane of section) in their appropriate sections.

   Step 5. If the sunbeam enters the window in section, also show it entering in plan. If the sunbeam is blocked by

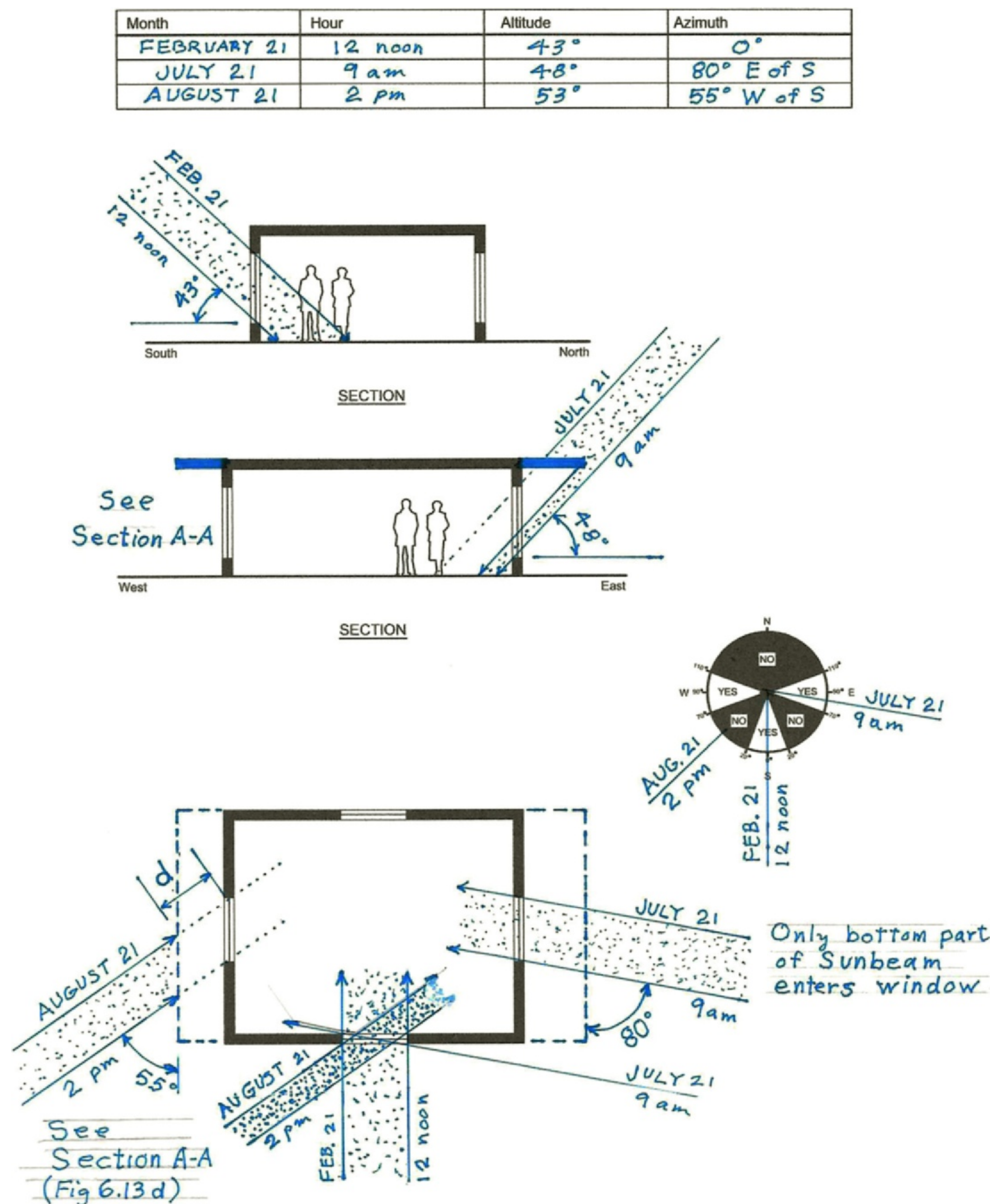


Figure 6.13c All sunbeams are shown on plan, but only those in the "yes" zone of the key plan can be shown in the appropriate section. From the section it is possible to determine which sunbeams are blocked by an overhang and which are not. Since the July 21, 2 p.m., sunbeam is more than 20 degrees out of the east-west section, a special section cut along the azimuth must be used, as shown in Fig. 6.13d. Because that section shows that the sunbeam is blocked, the sunbeam is shown in plan ending at the edge of the west overhang.

a shading device, show it on plan and section ending at the shading device (i.e., dashed line on plan).

Step 6. If a sunbeam was not in a "yes" zone on the key plan, then cut a special section through the window parallel to the sunbeam (Fig. 6.13d). Note, however, that the length of the overhang must be measured along the section cut as shown in the west window of Figure 6.13c. The length of overhang that the sun sees at that date and time is shown as length *d*. Because in that section the sunbeam can be drawn with complete accuracy, the section will reveal if the sunbeam is blocked or not.

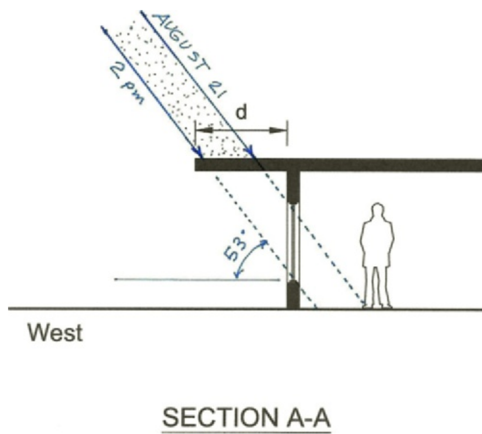


Figure 6.13d When important sunbeams are more than 20° out of the plane of standard sections, special sections must be cut parallel to those sunbeams to get accurate results. In this special section the apparent overhang length is "d," as also indicated in the plan.

The other challenge in drawing meaningful sunbeams is picking the days and times that are best for testing and demonstrating the solar design. The most often chosen days, and unfortunately the worst choices, are June 21 and December 21. The sun is highest in the sky on June 21 and therefore most easily shaded. Furthermore, June 21 does not represent the hottest time of the year, which occurs in July and August. Similarly, on December 21 the sun is lowest in the sky and is therefore least blocked by any overhang. And again, the coldest time of the year occurs in January and February and not around December 21.

To best understand the performance of a design, sunbeams should be drawn for the last day in the summer when it is still too hot and full shading is still desired and for the last day in the winter when it is still too cold and full exposure to sunlight is still desired. For internally dominated buildings these dates can be found in Table 9.5B and for envelope-dominated buildings in Table 9.5C. These two sunbeams when drawn for 12 noon will reveal how much the south windows are shaded during the whole overheated period and how much sun they can collect during the whole underheated period.

To learn more about the performance of east and west windows, also draw sunbeams for July 21 at 8 A.M. and 4 P.M. and January 21 at 9 A.M. and 3 P.M. To fully understand the performance of east and west windows, also draw sunbeams at 9 A.M. and 3 P.M. on the last days of the overheated and underheated periods of the year (the dates discussed in the previous paragraph).

Because it is difficult to understand solar geometry in two dimensions, sun-path models are worth making, and they are described next.

6.14 SUN-PATH MODELS

Three-dimensional models of the sun-path diagrams are especially helpful in understanding the complex geometry of sun angles (Fig. 6.14). For simplicity only the sun paths for June 21, March/September 21, and December 21 are shown. These models can help a designer better visualize how the sun will relate to a building located at the center of the sun-path model.

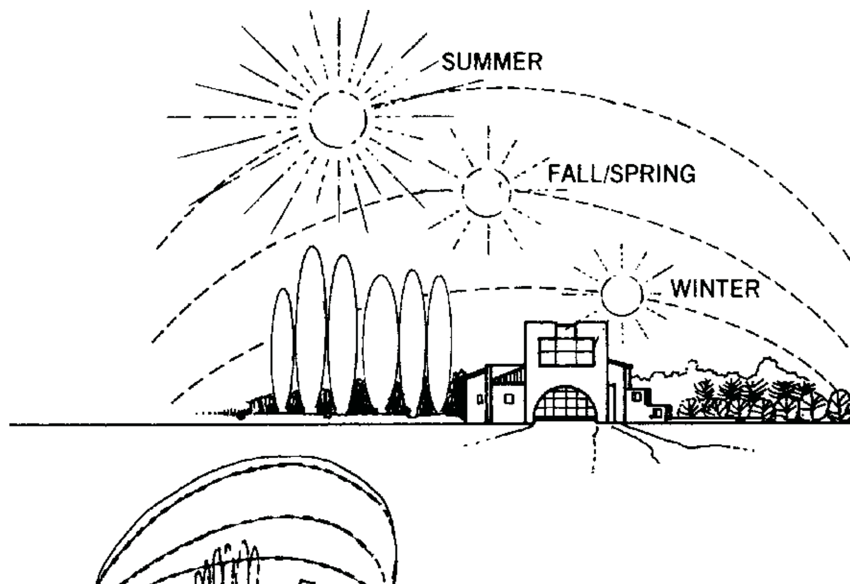


Figure 6.14 Various sun-path models are shown to illustrate how sun angles vary with latitude. In each case, the highest sun path is for June 21, the middle for March/September 21, and the lowest for December 21. Thus, the sun paths for all other months would be located between the highest and lowest sun paths.

The various models illustrate how sun paths vary with latitude. Models are shown for the special latitudes of the Equator at 0°, the Tropic of Cancer at 23.5° (the model is for 24°), the Arctic Circle at 66.5° (the model is for 64°), and the North Pole at 90°. Appendix F presents complete instructions and a set of charts required to create a sun-path model at 4° intervals of latitude. It is worthwhile to spend the fifteen minutes required to make one of these sun-path models for the latitude where a building is to be designed. Assume that the building to be designed is the size of a point located at the center of the sun-path model. The sun-path model can then be placed on the corner of the designer's table to be a reminder of where the sun is at different times of the day and year.

6.15 SOLAR HEAT GAIN

The intensity of solar radiation reaching the surface of the earth combined with its angle will determine the solar heating impact. Figures 6.15a and 6.15b show the heating impact on the four walls and roof of a building at 32° N latitude and Figures 6.15c and 6.15d show the impact at 48° N latitude.

Figure 6.15a shows how many Btu fall on each square foot every hour (W/m^2) on the four facades of a building oriented along the cardinal directions of the compass at 32° N latitude. The graph for each orientation shows a curve for both June 21 and December 21. Figure 6.15b shows the intensity of the solar radiation falling on a skylight (horizontal window) at 32° N latitude on June 21 and December 21.

The following are observations about the solar radiation graphs for a building at 32° N latitude:

1. The shaded areas indicate light coming only from the sky (i.e., no sunlight).
2. The south facade gets much more sunshine in December than in June, which is great for passive solar heating. After sunrise, the intensity of the sunshine increases very rapidly until it reaches its maximum at 12 noon.
3. As everywhere on the planet, the east and west facades receive the same amount of solar radiation unless modified by local conditions such as shading from a large building or regular morning fog. On June 21, the solar load on the east and west windows is much larger than on the south windows, and therefore, the east and west windows need much more shading than the south windows. The solar radiation on the east and west windows is large enough in the winter to make collecting it worthwhile.
4. The north facade receives enough solar radiation on June 21 to require shading if the building is to be low energy. On December 21, the north windows receive no direct sunlight but only a small amount of light from the sky.
5. A skylight receives more sunshine on June 21 than on December 21, which is the exact opposite of what is desired. However, at 32° the difference between summer and winter is not as great as at 48°. Thus, as one moves south of 32° on the planet, the difference in solar radiation received by a skylight between June 21 and December 21 quickly diminishes, making small skylights sometimes appropriate in the tropics and near tropical regions. Since at 32° the maximum intensity on a skylight on June 21 is about 25 percent greater than that on east or west windows, skylights if used at all need shading even more than east and west windows.

Figure 6.15c shows how many Btu fall on each square foot every hour (W/m^2) on the facades of a building aligned with the four cardinal directions of the compass at 48° N latitude. Figure 6.15d shows the impact on a skylight at 48° N latitude.

The following are observations about the solar radiation graphs for a building at 48° N latitude:

1. The shaded areas indicate light coming only from the sky (i.e., no direct sunlight).
2. The south windows get much more sunlight in the winter than in the summer, but there is still a significant amount of summer sun that must be shaded.
3. As always, the solar heat gain on east and west windows is the same unless modified by local conditions such as shade from a large building or morning fog. The summer heat gain on east and west windows is very large and therefore must be reduced significantly. In the winter, however, the solar intensity on east and west windows is quite small and does not warrant a large effort to collect it.
4. Although the north windows receive a modest amount of solar radiation in the summer, they should be shaded in any low energy building. In the winter, the north windows receive very little solar radiation, and it is all from the sky.
5. Because skylights receive about nine times more solar radiation on June 21 than on December 21, south-facing clerestories should be used instead of skylights at 48°.

Moving from 32° to 48° N latitude, the sun is 16° lower in the sky every day at 12 noon. As a result, there are several important changes in the heat gain impact on a building:

1. South windows at 48° N latitude receive a little less sunlight in the winter but much more in the summer than do south windows at 32° N latitude. Thus significant shading is needed on south windows even in northern latitudes.
2. East and west windows at 48° N latitude receive much more sunshine in the summer than do south windows. Thus, east and west windows need even more shading than south windows in northern latitudes. However, at 48° N latitude, the east and west windows get significantly less

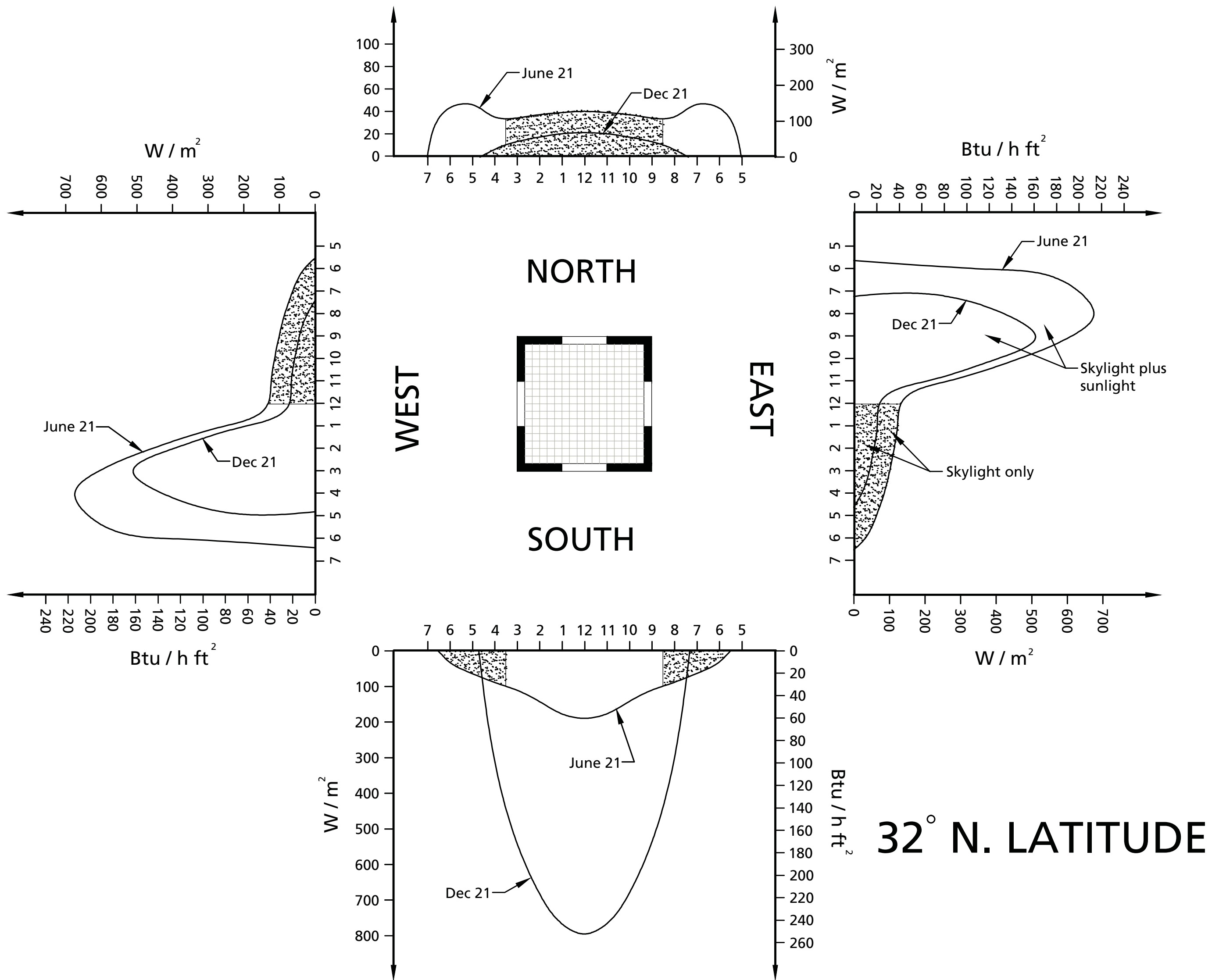
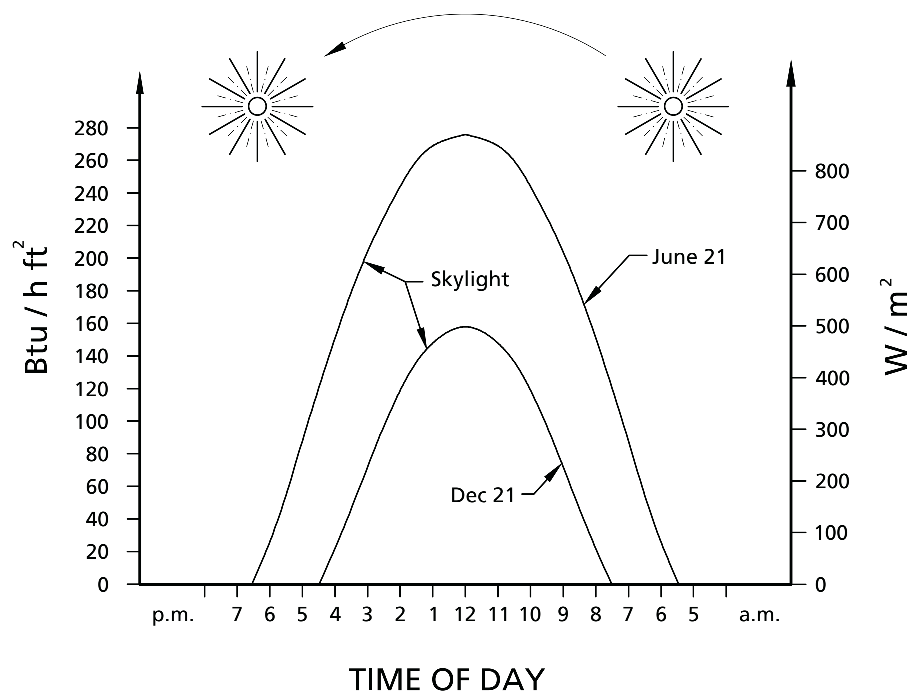
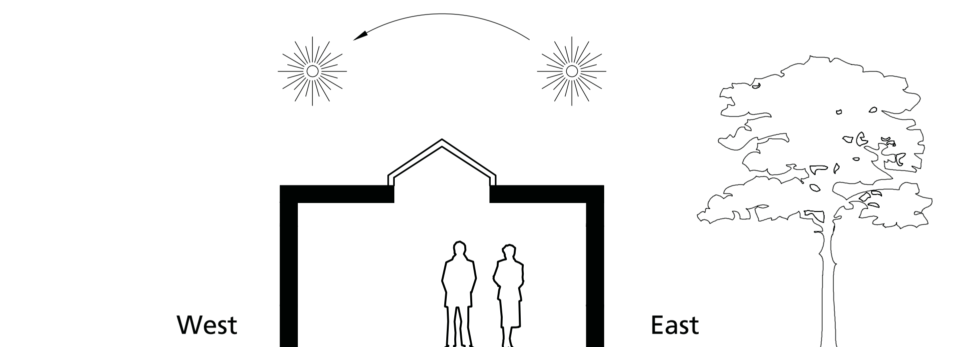


Figure 6.15a These graphs show how much solar radiation falls on each facade of a building on June 21 and December 21 at 32° N latitude. South windows receive much more sun on December 21 than on June 21, which is great for passive solar heating. East and west windows receive too much sun on June 21, which is a major problem. However, east and west windows still receive a significant amount of sunlight on December 21, which can be useful. North windows collect about the same amount of solar radiation as south windows on June 21.





32° N. LATITUDE

Figure 6.15b At 32° N latitude, skylights receive significantly more sun on June 21 than on December 21, which is the reverse of what we want. On June 21, skylights receive more sunlight than either east or west windows, which indicates that skylights are a major source of overheating.

sunshine on December 21 than do east and west windows at 32° N, making them less valuable for collecting winter sun.

3. At 48° N latitude, north windows receive almost the same solar radiation in the summer as do north windows at 32° N latitude.
4. Skylights at 48° N latitude receive about the same amount of solar radiation as do skylights at 32° N latitude on June 21. Thus, skylights are a major cause of overheating at all latitudes. However, in the winter the skylights at 48° N latitude get much less sunlight than do skylights at 32° N, making them even less appropriate at 48° than at 32°.

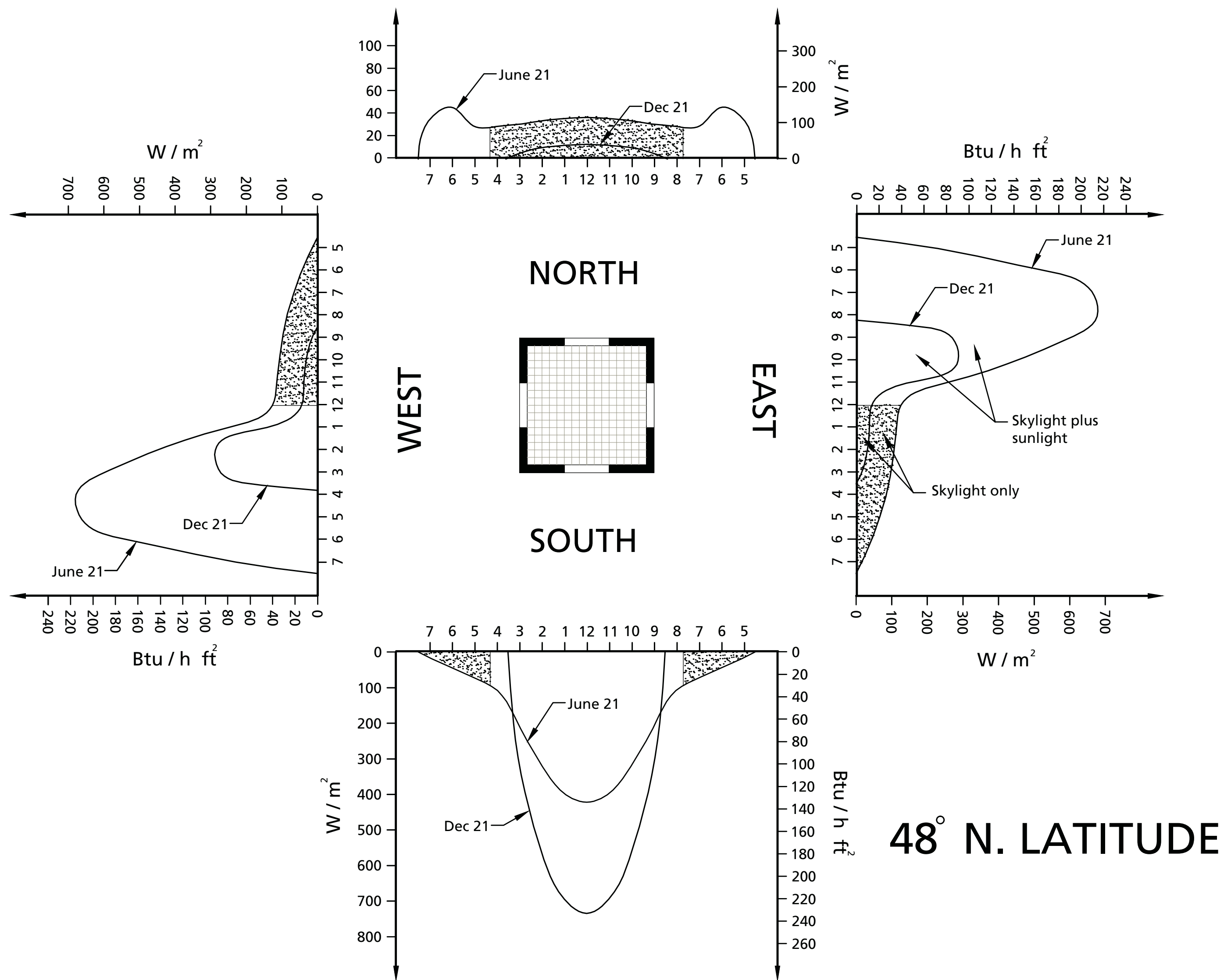
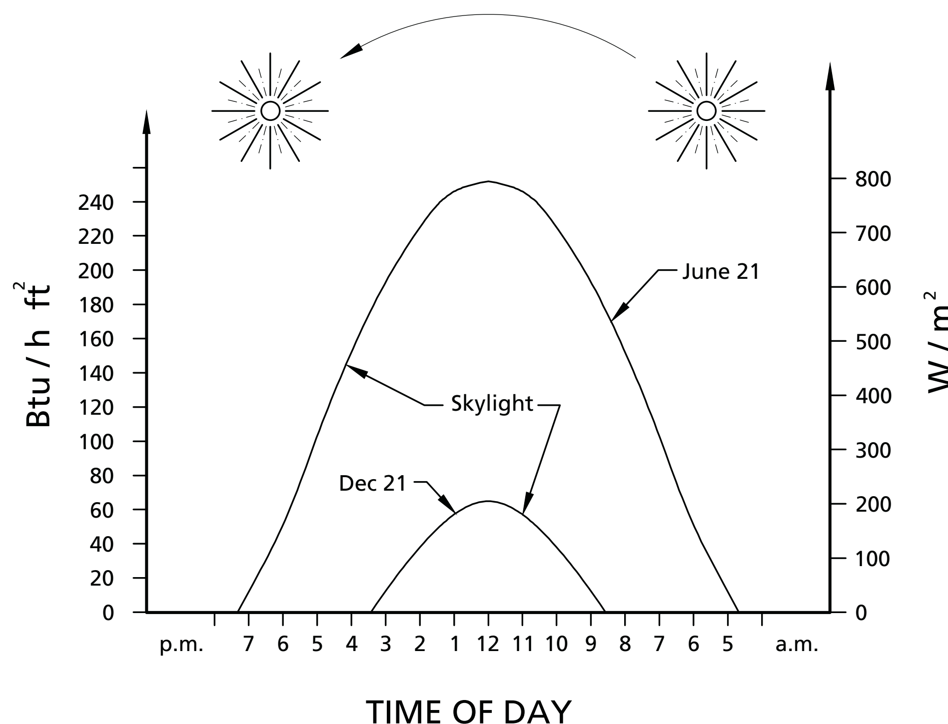
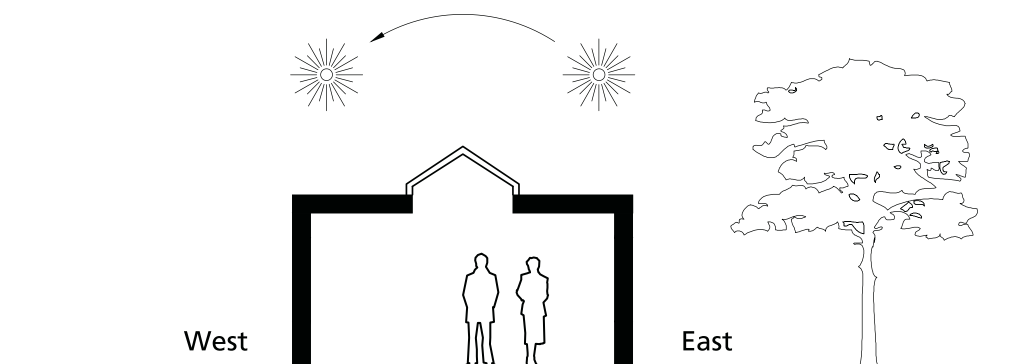


Figure 6.15c These graphs show how much solar radiation falls on each facade of a building on June 21 and on December 21 at 48° N latitude. South windows receive more sunlight on December 21 than on June 21, which is great for passive solar heating. Because they receive too much sunlight on June 21, they require significant shading. East or west windows collect much more sun than south windows on June 21, which demonstrates the importance of shading east and west windows. However, they receive too little sunshine on December 21 to make them valuable sources for passive solar. The solar radiation on north windows on June 21 is about half direct and half from the sky, and on December 21 north windows receive only a very small amount of solar radiation, all of which comes from the sky.





48° N. LATITUDE

Figure 6.15d At 48° N latitude, skylights collect much more sun on June 21 than on December 21, which is the exact opposite of what is needed. South-facing clerestories are therefore a better alternative.

6.16 SOLAR SITE-EVALUATION TOOLS

A solar building on a site that does not have access to the sun is a total disaster. Fortunately, there are good tools available for analyzing a site with regard to solar access. Appendix H presents information on how to buy or build your own low-cost site-evaluation tool similar to the one shown in Figure 6.16. The Solar Pathfinder and the Sun Eye are commercially available site-evaluation tools.

As Figure 6.16 illustrates, the landscape to the south of the proposed window or solar collector site is viewed through the device in such

a manner that the sun-path diagrams are superimposed on what is seen. It is then immediately clear in the skydome to what extent the solar window is blocked.

One serious drawback of most site evaluation tools is that they indicate the solar access for only the spot where the tools are used. They cannot easily determine the solar access for the roof of a proposed multistory building. The one partial exception is the Sun Eye, which can be raised on a pole to the roof of a two-story building. There is, however, a solution to this problem. A scale model of the site analyzed with a heliodon is an excellent method of evaluating the site for solar access. The scale model can then also be used for the design and presentation stages of the building project.

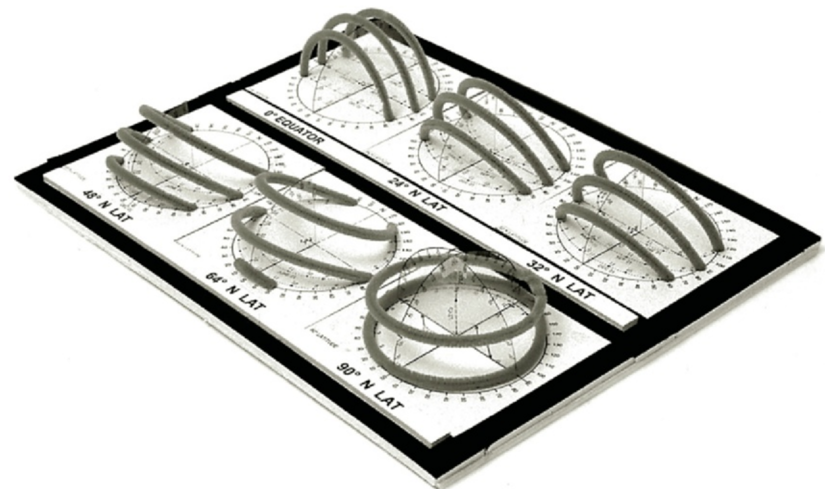


Figure 6.16 A vertical sun-path diagram is used as part of this solar-site evaluation tool.

6.17 HELIODONS

To simulate shade, shadows, sun penetration, and solar access on a scale model, a device called a heliodon is used. A heliodon simulates the relationship between the sun and a building. The three variables that affect this relationship are latitude, time of year, and time of day. Every heliodon has a light source, an artificial ground plane, and three adjustments so that the light will strike the ground plane at the proper angle corresponding to the latitude, time of year, and time of day desired. In the heliodon shown in Fig. 6.17a, we can see the light moving on a circular track to simulate time of day. The track slides forward and back to simulate time of year, and it is tilted to simulate the latitude.

Heliodons are excellent tools for creating solar-responsive designs. Because of the compound angles created by sunrays, graphical tools are awkward and/or misleading. Experience has shown that although computer models are powerful, physical models are still better. It is well known that a picture is worth a thousand words, but it is less well known that a model is worth a thousand

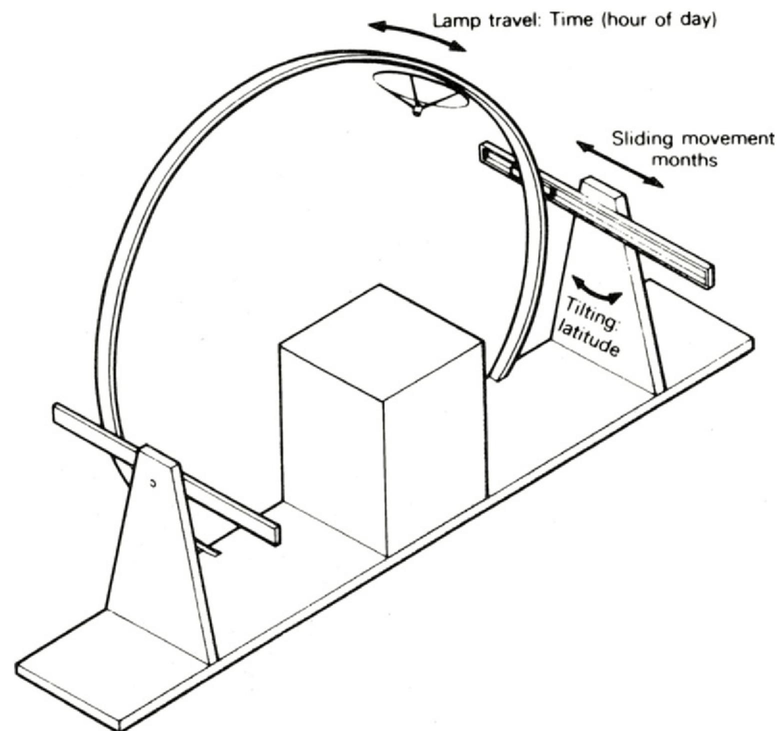


Figure 6.17a This type of heliodon ("solarscope B") was developed by Szokolay. (From *Environmental Science Handbook for Architects and Builders*, by S. V. Szokolay, copyright John Wiley, 1980.)

pictures. Physical modeling is very easy to understand, infinitely flexible, and inexpensive once you have a heliodon, and some heliodons are very inexpensive.

As powerful and flexible tools, heliodons have many uses in both teaching and design. Heliodons are excellent tools for teaching both solar geometry and specific design strategies like overhangs and fins for shading. In the design process they have several functions:

1. Site analysis for determining solar access
2. Design of the building form
3. Design of specific features such as shading devices
4. Analysis of alternative designs
5. Presentation either live or through photographs or videos

Because heliodons are such powerful tools, the author believes that every architecture firm and every architecture school should have at least one. For this reason, Appendix I gives information on how to build or where to buy a heliodon. Since there are many kinds of heliodons, the advantages and disadvantages of the major ones are discussed below.

The tabletop heliodon shown in Figure 6.17b consists of a model stand, which rests on a table, and a clip-on lamp, which is supported by the edge of an ordinary door. The adjustment for time of year is made by moving the light up or down along the door edge. The model stand is tilted for the latitude and rotated about a vertical axis for the time-of-day adjustment.

This heliodon is very easy and inexpensive to construct (about $30). Another virtue of this heliodon is that even though it can accommodate large models, it is lightweight and compact, making it easy to store or carry. Because of the many virtues of this type of heliodon, complete instructions for its use and construction are included in Appendix I.

This heliodon, unlike the ones described later, can be taken outdoors and used with the parallel light from the sun. Consequently, the use of sundials for model testing is explained next.

Because people evolved to understand the physical reality around them, the brain will always find physical models especially easy to understand!

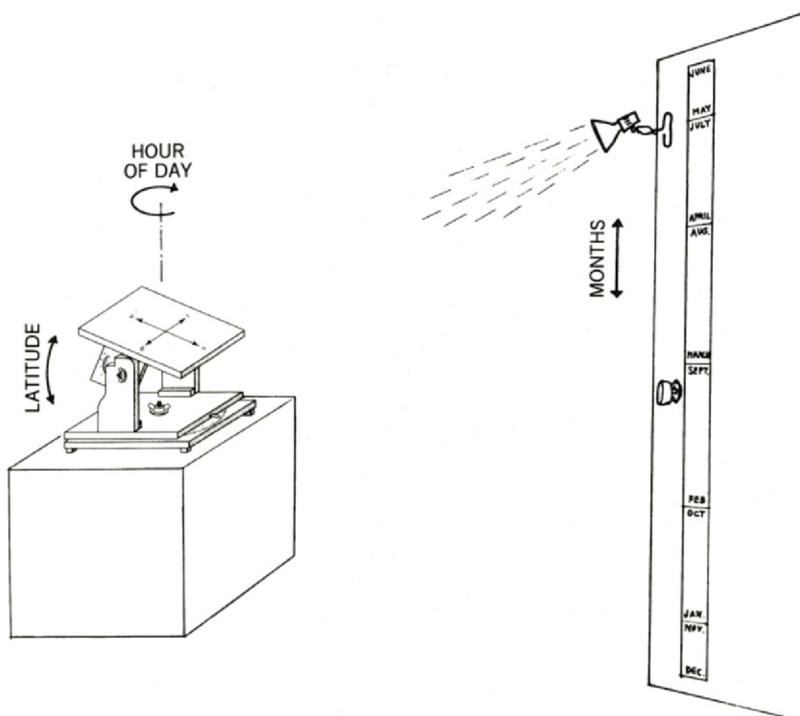


Figure 6.17b This tabletop heliodon is a practical, low cost, and appropriate tool for every architect, planner, developer, and landscape architect.

6.18 SUNDIALS FOR MODEL TESTING

The least expensive way to test models for shading, solar access, and daylighting is to use a sundial (Fig. 6.18). Instead of using a sundial the conventional way, which is to determine the time of day and year, the sundial is used to rotate and tilt a model so that the shadows correspond to the time of day and year to be analyzed. Thus, a sundial would be mounted on a model so that its south and that of the model align. The model along with the sundial is then rotated and tilted until the shadow of the gnomon (peg) points to the time and day to be analyzed. Instructions for making sundials for various latitudes can be found in Appendix E. The tabletop heliodon can be used to hold the model at the appropriate orientation and tilt. See the "Alternate Mode of Use of the Heliodon" in Section I.4 of Appendix I for instructions on how to use the sundial in conjunction with the heliodon.

Sundials have important advantages and disadvantages in regard to testing physical models. When one uses the sun as a source of light, great accuracy can be achieved in modeling shadows and sunbeams. However, this mode of testing is limited to daytime on sunny days, which are not common in some climates and some times of the year. A slightly less accurate but sometimes more practical use of the sundial is in conjunction with an electric light source, such as a slide or video projector at the end of a corridor. The farther the light source is from the model, the more parallel are the light rays.

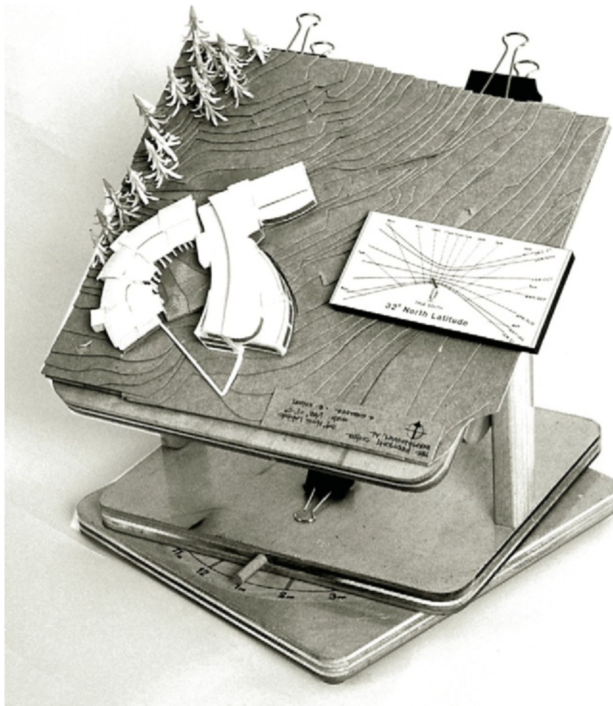


Figure 6.18 Sundials can be used to test models either under sunlight or a remote electric light source.

The author believes that sundials are great for making accurate photographs of finished designs and for studying daylight models outdoors, while conceptually clear heliodons are better during the design process for understanding solar access and shading.

6.19 CONCEPTUALLY CLEAR HELIODONS

Two new types of heliodons have been developed by the author at Auburn University. They are three-dimensional models of the solar window, with each month's sun path represented by an arch. Thus, even before any lights are turned on, the heliodons are powerful tools to teach solar geometry. Because the ground plane (model) is always horizontal, these heliodons simulate our everyday experience of the sun revolving over a building site. They make solar geometry so simple that even a child can understand it. Because of this clarity, they are called conceptually clear heliodons.

The first conceptually clear heliodon to be developed was the Sun Simulator (Fig. 6.19a). It was built for the latitude of Auburn (32°) and is about 15 ft (4.5 m) in diameter so that large models can be tested in front of a whole class. Because of the annual symmetry, all twelve months can be simulated with only seven arches, as can be seen on any sun-path diagram. There is one light for each hour of the day that can be conveniently switched on to make model testing very easy. To increase the range of latitudes that can be simulated, the model table can be tilted up to 5° each way. Conceptual clarity is not lost if the model is tilted only a few degrees. This adjustment allows the testing of models from as far south as Miami to as far north as San Francisco. Complete CAD drawings are available for free from the author to build such a heliodon for any latitude (see Appendix I).

The Sun Emulator heliodon was developed by the author for those schools and architectural firms that don't have the room or resources to build their own heliodon (Fig. 6.19b). The Sun Emulator was designed to be completely assembled at the factory, and it is as large as possible while still fitting through a 3 ft (0.9 m) door. It can simulate any latitude from the equator to the poles and still have the model's ground plane completely horizontal. Because the lights are only 3 ft (0.9 m) from the center of the table, models need to be small for accuracy. For more information about the Sun Emulator, see Appendix I.

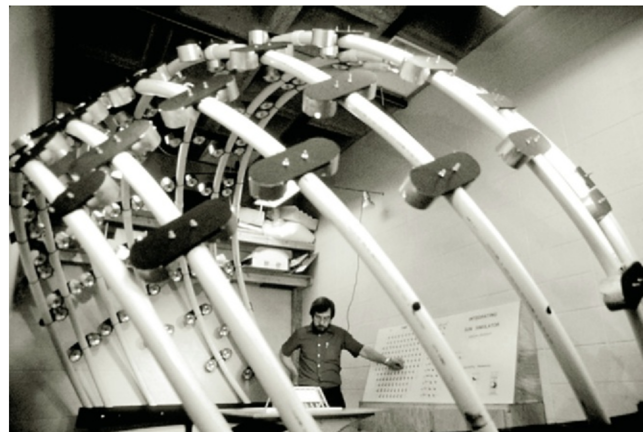


Figure 6.19a The Sun Simulator heliodon was developed by the author at Auburn University, Alabama.



Figure 6.19b The Sun Emulator heliodon was developed for those architecture schools and firms that do not have the room for a permanently fixed heliodon such as the Sun Simulator. The conceptually clear Sun Emulator is completely assembled at the factory and, when stored, requires a floor area of only 3 × 6 ft (1 × 2 m).

6.20 CONCLUSION

Because solar geometry is very complicated, the author highly recommends a heliodon for every architect, planner, and developer, as well as for schools of architecture and science museums. There is an appropriate model and price for every situation.

The concepts presented in this chapter on the relationship between the sun and the earth are fundamental for an understanding of much of this book. The chapters on passive and active solar energy, shading, passive cooling, daylighting, and photovoltaics depend heavily on the information presented here.

With so many solar-responsive design strategies to choose from, which ones should be used and is there any priority in the selection for the designer? The concept of "pick the low-hanging fruit first" is always smart advice (see again Fig. 2.14). In this case, the advice is "pick the low-hanging solar-responsive design strategies first." The solar-responsive design "fruits" will now be introduced in the order in which they should be picked. They are described in much more detail in later chapters.

Building Orientation: The lowest-hanging and most important solar "fruit" is orientation. It is critical for just about every other solar strategy, and it is free. If all windows face south and north, solar energy collection, shading, and daylighting can all be maximized at great savings of both energy and money. For example, in a case where the site allows it, rotating a building 90° can reduce the energy consumption for heating, cooling, and lighting as much as 40 percent

for free! Orientation is a key factor in Chapters 7, 8, 9, and 13.

Color: The greenest color is white, because it significantly reduces the heat gain of buildings, cities, and the planet. White walls are 30 percent cooler than dark walls such as common brick, and white roofs are 50 percent cooler than black roofs. Of course, the savings are greatest in very hot climates, but white walls and roofs are appropriate for almost all climates. Again, much energy and money can be saved. Color is discussed further in Section 9.21.

Window placement: Although some designers believe that each facade should look the same, that belief is nonsustainable, and of dubious aesthetic validity. After all, people do not look the same from all sides. The ideal design would have only south and north windows and no east or west windows. When that is not possible, the number of east and west windows should be minimized and the number or north and south windows maximized. For example, if half of the east and west windows of a proposed design were moved to the north and south facades, the total number of windows would remain the same, but energy consumption and its cost would be significantly reduced at no cost. This solar fruit is especially critical if the building as a whole cannot be oriented in the ideal direction. Furthermore, in the case where a building has to have the worst orientation with the long facades facing east and west, those walls can be designed in a sawtooth fashion so that the windows on the east and west facades can face north or south (see Section 9.3).

Window Size: Making windows on the east and west facades smaller than those on the north and south facades is another free strategy to save energy and money. Furthermore, the windows on the east and west facades should be placed in the "landscape" rather than "portrait" position, because low and wide windows are easier to shade than tall and narrow windows.

Shading: Since air-conditioning is a major energy consumer and since it is becoming an ever larger percent of the energy use of buildings on a global scale, shading is increasingly important in creating a sustainable world. Although not free, shading is almost always cost-effective, and it is always the right thing to do. Shading is covered in detail in Chapter 9.

Passive Solar: The full name of this strategy is passive solar space heating, and it is accomplished by the design of the building rather than any mechanical heating system. Depending on which passive solar system is used, the cost can vary from zero to substantial. Since reducing the fossil energy used for heating is always a sustainable strategy, some passive solar system should always be used in buildings that have heating systems and have access to the winter sun. It is described in detail in Chapter 7.

Solar Chimney: Although collecting solar energy to cool a building may seem to be a contradiction, it can be done in both active and passive modes. A solar chimney is a passive device for ventilating a building in the summer by using the heat of the sun. It is described further in Section 10.16.

Daylighting: About 40 percent of the energy consumption of office buildings is for lighting. Daylighting can significantly reduce that amount. The cost of a daylighting system can vary from zero to substantial depending on how it is done. It costs zero when the low-hanging fruits of building orientation, window placement, and window size are used appropriately. In addition, windows should be placed high on a wall so that daylight penetrates farther into the building. Daylighting is discussed in detail in Chapter 13.

Ventilation Preheating: Much energy is needed for heating ventilation air in cold climates, and the energy consumption is especially large for building types like hospitals that require large amounts of fresh outdoor air. Inexpensive transpired collectors can use the sun to preheat the fresh but cold outdoor air (see Section 8.24).

Active Solar: Active solar systems use collector panels to harvest the heat of the sun for heating water or air, and they use fans or pumps to move that heat indoors. Most active systems heat domestic (sanitary) water for cleaning and washing. Active systems can also be used to heat a building, especially if the limited solar access prevents the use of passive solar but is available high on the roof. These heating systems are described in Chapter 8. Active solar systems can also be used to run absorption refrigeration systems to cool buildings (see Section 16.9).

Photovoltaics (PV): When referred to as solar panels, it is not clear whether the panels create solar electricity or solar thermal (hot water or hot air). Thus, the terms "solar cells" or "photovoltaics" (PV) should be used. PV is a wonderful method for harvesting the sun to create that most useful form of energy, electricity. However, PV is the highest solar fruit because at present it is still expensive. Since money should be spent to achieve the maximum benefit, at present that means using all of the lower-hanging fruit before PV. As cost of PV is lowered further, PV may well move down on the solar-responsive design tree, but it will never beat those strategies that are free, making them the lowest-hanging fruit. However, buildings and cities should be designed to accept PV for the time when it becomes affordable for everyone.

Because heating, cooling, and lighting are major energy users, and because they are all heavily impacted by the sun, a building or a city cannot be sustainable unless they are solar responsive!

KEY IDEAS OF CHAPTER 6

1. Solar radiation reaching the earth's surface consists of about 45 percent visible, about 50 percent short-wave infrared (heat), and about 5 percent ultraviolet radiation.
2. Winter is the result of a shorter number of daylight hours, the filtering effect of lower sun angles, and the cosine law.
3. The sun is 47° higher in the sky in the summer than in the winter at 12 noon.
4. Sun angles are defined by altitude and azimuth angles. The altitude is a vertical angle measured from the horizontal and the azimuth is a horizontal angle measured from south.
5. The solar window is that part of the sky dome through which the sun shines.
6. Sun-path diagrams present both the pattern of the sun's motion across the sky and specific sun-angle data.
7. Sun-path models and sundials are simple tools for achieving solar-responsive architecture.
8. The solar access to a site can be determined by site evaluation tools.
9. A heliodon is a powerful tool for achieving solar-responsive architecture.
10. Pick the lowest hanging solar responsive design strategy first.

Resources

HELIODONS

For more information on how to build or purchase a heliodon, see Appendix I.

FURTHER READING

(See the Bibliography in the back of the book for full citations.)

Anderson, B. *Solar Energy*.
Bennett, R. *Sun Angles for Design*.
Knowles, R. L. *Ritual House*.
Mazria, E. *The Passive Solar Energy Book*.
Stein, B., J. S. Reynolds, W. T., Grondzik, and A. G. Kwok. *Mechanical and Electrical Equipment for Buildings*.

PAPERS

Knowles, R. L. "Rhythm and Ritual," www.rcf.usc.edu/~rknowles
———. "On Being the Right Size," www.rcf.usc.edu/~rknowles

CHAPTER 7

PASSIVE SOLAR

The useful practice of the "Ancients" should be employed on the site so that loggias should be filled with winter sun, but shaded in the summer.
Leone Battista Alberti from his treatise* De Re Aedificatoria*, 1452, the first modern work on architecture, which influenced the development of the Renaissance architectural style.

Orientation is 80 percent of passive solar design.
Doug Balcomb, solar scientist

The south facade is a goldmine for harvesting winter sun, easy summer shading, and year-round quality daylighting.
Anonymous

7.1 HISTORY

Although the ancient Greeks used the sun to heat their homes, the benefits were modest because much of the captured heat escaped again through the open windows during the day. The efficient and practical Romans first solved this problem by using glass in their windows sometime around A.D. 50. The glass created an efficient heat trap by what we now call the greenhouse effect. The idea worked so well that the Romans found a variety of uses for it.

The upper classes often added a sunroom (*heliocaminus*) to their villas. Greenhouses produced fruits and vegetables year-round. The later, more modern version of the Roman baths usually faced the winter sunset (southwest) when the solar heat was most needed. Solar heating was important enough that Roman architects such as Vitruvius wrote about it in their books.

With the fall of Rome, the use of solar energy declined, and Europe entered the Dark Ages. During the Renaissance, architects such as Palladio read and appreciated the advice of the Roman architect Vitruvius. Palladio utilized such classical principles as placing summer rooms on the north side and winter rooms on the south side of a building. Unfortunately, northern Europe copied the style but not the principles that guided Palladio.

The seventeenth century in northern Europe saw a revival of solar heating, but not for people. Exotic plants from newly discovered lands, and the appetite of a sizable upper class for oranges and other warm-climate fruits, created a need for greenhouses (Fig. 7.1a). Eventually, those greenhouses that were attached to the main building became known as conservatories (see Fig. 7.1b). These, like our modern sunspaces, were used for growing plants, to add space to the living area, and to help heat the main house in the winter. This use of the sun, however, was reserved for the rich.



Figure 7.1a The orangery on the grounds of the royal palace in Prague, the Czech Republic, has an all-glass south facade and an opaque roof, which are typical of the greenhouses that became popular in the eighteenth century.

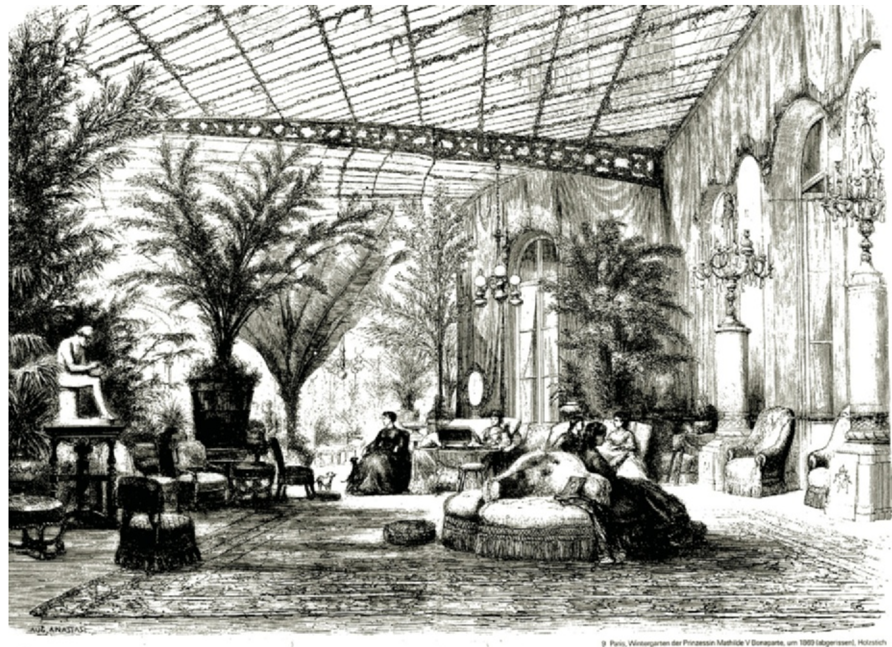


Figure 7.1b Conservatories supplied plants, heat, and extra living space for the upper classes in nineteenth-century Europe. Conservatory of Princess Mathilde Bonaparte, Paris, about 1869. From *Uber Land und Meer*, Allgemeine Illustrierte Zeitung, 1868.

The idea of solar heating for everyone did not start in Europe until the 1920s. In Germany, housing projects were designed to take advantage of the sun. Walter Gropius of the Bauhaus was a leading supporter of this new movement. The research and accumulated experience with solar design then slowly made its way across the Atlantic with men like Gropius and Marcel Breuer.

7.2 SOLAR IN AMERICA

Passive solar design also has Native American roots. Many of the early Native American settlements in the Southwest show a remarkable understanding of passive solar principles. One of the most interesting is Pueblo Bonito (Fig. 7.2a), where the housing in the south-facing semicircular village stepped up to give each home

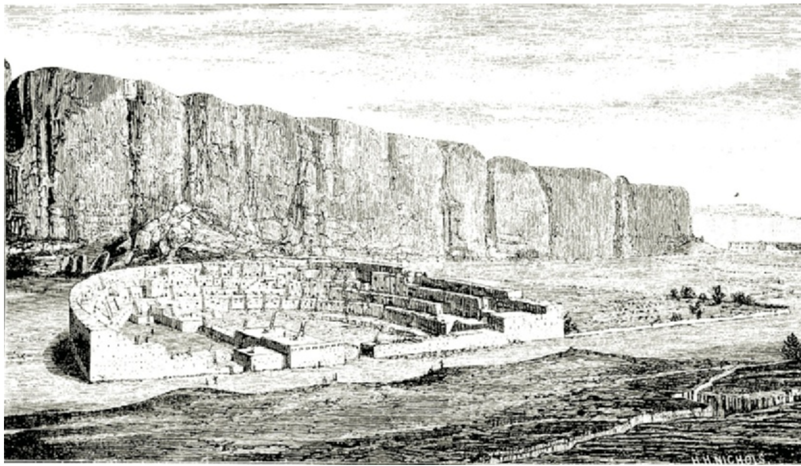


Figure 7.2a This is an artistic reconstruction of Pueblo Bonito, Chaco Canyon, New Mexico. Built about A.D.1000, Pueblo Bonito is an example of an indigenous American solar village. (From *Houses and House-Life of the American Aborigines*, by Lewis Morgan [contributions to *North American Ethnology*. Vol. 4], U.S. Department of the Interior/U.S. G.P.O., 1881.)



Figure 7.2b The New England saltbox faced the sun and turned its back to the cold northern winds. (From *Regional Guidelines for Building Passive Energy Conserving Homes*, by AIA Research Corporation, U.S. G.P.O., 1980.)

full access to the sun, and the massive construction stored the heat for nighttime use.

Some of the colonial buildings in New England also show an appreciation of good orientation. The saltbox, as shown in Fig. 7.2b, has a two-story wall with numerous windows facing south to catch the winter sun. The one-story north wall had few windows and a long roof to deflect the cold winter winds.

Aside from these early examples, the heating of homes with the sun made slow progress until the 1930s, when a number of different American architects started to explore the potential of solar heating. One of the leaders was George Fred Keck, who built many successful solar homes (Fig. 7.2c). The pioneering work of these American architects, the influence of the immigrant Europeans, and the memory of the wartime fuel shortages made solar heating very popular during the initial housing boom at the end of World War II. But the slightly higher initial cost of solar homes and the continually falling price of fuels resulted in public indifference to solar heating by the late 1950s.

7.3 SOLAR HEMICYCLE

One of the most interesting solar homes built during this time was the Jacobs II House (Fig. 7.3a), designed

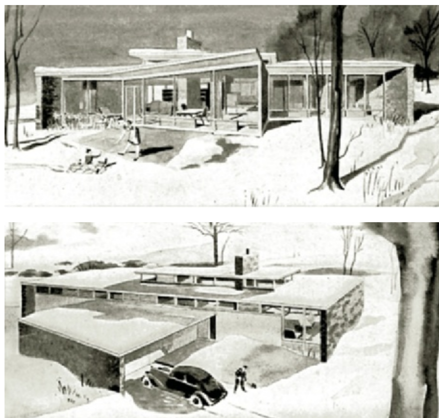


Figure 7.2c One of the first modern solar houses in America was designed by architect George Fred Keck in Chicago in the 1940s. (Used by permission of Pilkington North America, Inc.)



Figure 7.3a The Jacobs II House was designed by architect Frank Lloyd Wright and built in Madison, Wisconsin, circa 1948. (Photograph by Ezra Stoller © Esto.)

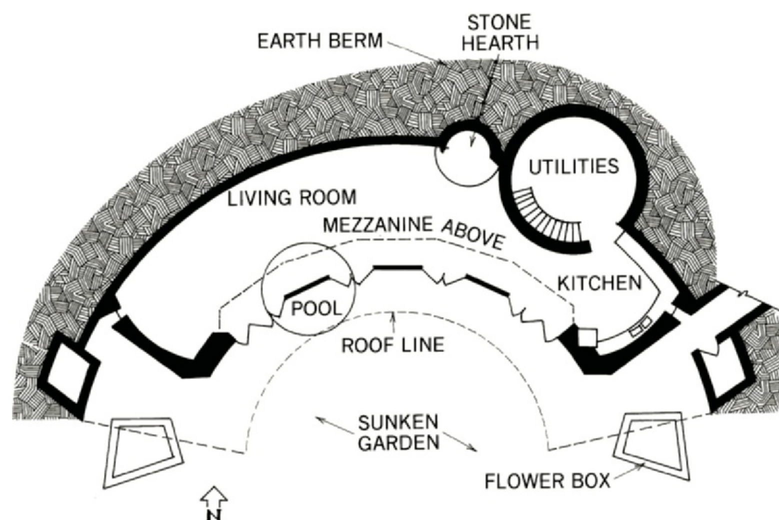


Figure 7.3b Plan of the Jacobs II house.

by Frank Lloyd Wright. Figure 7.3b shows a floor plan of this house, which Wright called a solar hemicycle. As usual, Wright was ahead of his time, because this building would in many ways make a fine passive home by present-day standards. For example, most of the glazing faces the winter sun but is well shaded from the summer sun by a 6 ft (1.8 m) overhang (Fig. 7.3c). Plenty of thermal mass, in the form of stone walls and a concrete floor slab, stores heat for the night and prevents overheating during the day (Fig. 7.3d). The building is insulated to reduce heat loss, and an earth berm protects the northern side. The exposed stone walls are cavity walls filled with vermiculite insulation. Windows on opposite sides of the building allow cross ventilation during the summer.

Like most of Wright's work, the design of this house is very well integrated. For example, the curved walls not only create a sheltered patio but also effectively resist the pressure of the earth berm, just as a curved dam resists the pressure of the water behind it. The abundant irregularly laid stone walls supply the thermal mass while relating the interior to the natural environment of the building site. Successfully integrating

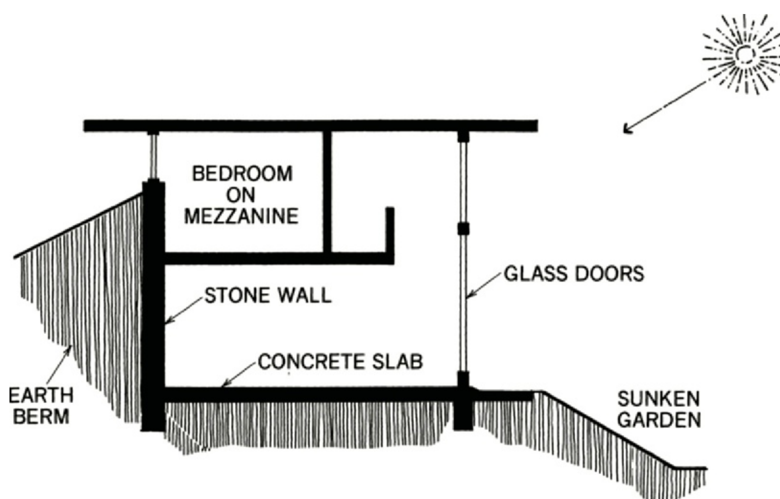


Figure 7.3c Section of the Jacobs II house.



Figure 7.3d This interior view of the Jacobs II House shows the two-story south-facing window wall, the concrete floor, and the stone walls for storing heat. (Photograph by Ezra Stoller © Esto).

the psychological and functional demands seems to produce the best architecture. This is what the truly great architects have in common.

7.4 LATEST REDISCOVERY OF PASSIVE SOLAR

From the late 1950s until the mid-1970s, it was widely assumed that active solar systems, with their mechanical gadgets, had the greatest potential for harnessing the sun. Slowly, however, it was realized that using active collectors for space heating would add significantly to the first costs of a home, while passive solar heating could be achieved with little or no additional first costs. It also became apparent that passive solar systems had lower maintenance and higher reliability than active systems.

Possibly the greatest advantage of passive solar is that it results in a more pleasant indoor environment, while active collectors only supply heat. The Human Services Field Office in Taos, New Mexico, is a pleasant place to work because of the abundance of sunlight that enters, especially in the winter (Fig. 7.4a). A sawtooth arrangement on the east and west walls enables the windows on those facades to also face south. There are also continuous clerestory windows across the whole roof so that even interior rooms have access to the sun. Black-painted water drums just inside the clerestory windows store heat for nighttime use, while insulated shutters reduce the heat loss.

Much of the renewed interest in passive solar occurred in New Mexico not only because of the plentiful sun but also because of the presence of a community of people who were willing to experiment with a different lifestyle. An example is the idealistic developer Wayne Nichols, who built many solar houses, including the well-known Balcomb House, described later. As so often happens, successful experiments in alternate lifestyles are later adopted by the mainstream culture. Passive solar is now being accepted by the established culture because it has proved to be a very good idea.



Figure 7.4a The Human Services Field Office, Taos, New Mexico (1979), has all of its windows facing 20° east of south to take advantage of the winter morning sun. The clerestory windows, which cover the whole roof, supply both daylight and solar heat.



Figure 7.4b Integrated passive and hybrid solar multiple housing, Berlin, 1988. (Courtesy of and copyright Institute fur Bau-, Umwelt- und Solar Forschung.)

Passive solar heating is also gaining popularity in other countries. Successful passive solar houses are even being built in climates with cloudy and gloomy weather, such as northern Germany at a latitude of 54° (Fig. 7.4b). This is the same latitude as that of southern Alaska. The success of passive buildings in so many different climates is a good indication of the validity of this approach to design.

Passive solar also provides security from power interruptions and the possibility of extremely high energy costs. There is a growing conviction that buildings should be designed to be resilient. With so many benefits, passive solar should be a fundamental part of every design for a building that has access to the winter sun.

7.5 PASSIVE SOLAR

"Passive solar" refers to a system that collects, stores, and redistributes solar energy without the use of fans, pumps, or complex controllers. It functions by relying on the integrated approach to building design, where the basic building elements, such as windows, walls, and floors, have as many different functions

as possible. For example, the walls not only hold up the roof and keep out the weather but also act as heat-storage and heat-radiating elements. In this way, the various components of a building simultaneously satisfy architectural, structural, and energy requirements.

Every passive solar heating system has at least two elements: a collector consisting of south-facing glazing and an energy-storage element that usually consists of thermal mass, such as rock or water.

Depending on the relationship of these two elements, there are several possible types of passive solar systems. Figure 7.5a illustrates the three main concepts:

1. Direct gain
2. Trombe wall (indirect gain)
3. Sunspace (isolated gain)

Each of these popular space-heating concepts will be discussed in more detail. This chapter will conclude with a discussion of a few less common passive space-heating systems.

Passive solar is part of sustainable design accomplished through the three-tier design approach (Fig. 7.5b). The first tier consists of minimizing heat loss through the building envelope by proper insulation, airtightness, and surface-area-to-volume ratios. The better the architect designs for heat retention, the less heating will be required. The second tier, which consists of harvesting the sun's energy by passive means, is explained in this chapter. The mechanical equipment and fossil energy of the third tier are needed only to supply the small amount of heating not provided by tiers one and two. A passive solar building can provide 60 to 80 percent of the required heating in most of the United States.

It is important to realize that a passive solar system does more than just heat the building. Most importantly, it provides security because the temperature inside a passive solar building will be much higher than a standard building in case of an extended power failure in the winter. Thus, passive solar is part of resilient design. Passive solar also provides daylighting and a healthy exposure to sunlight. Lastly, the mass needed to store heat can usually also be used for passive cooling in the summer.

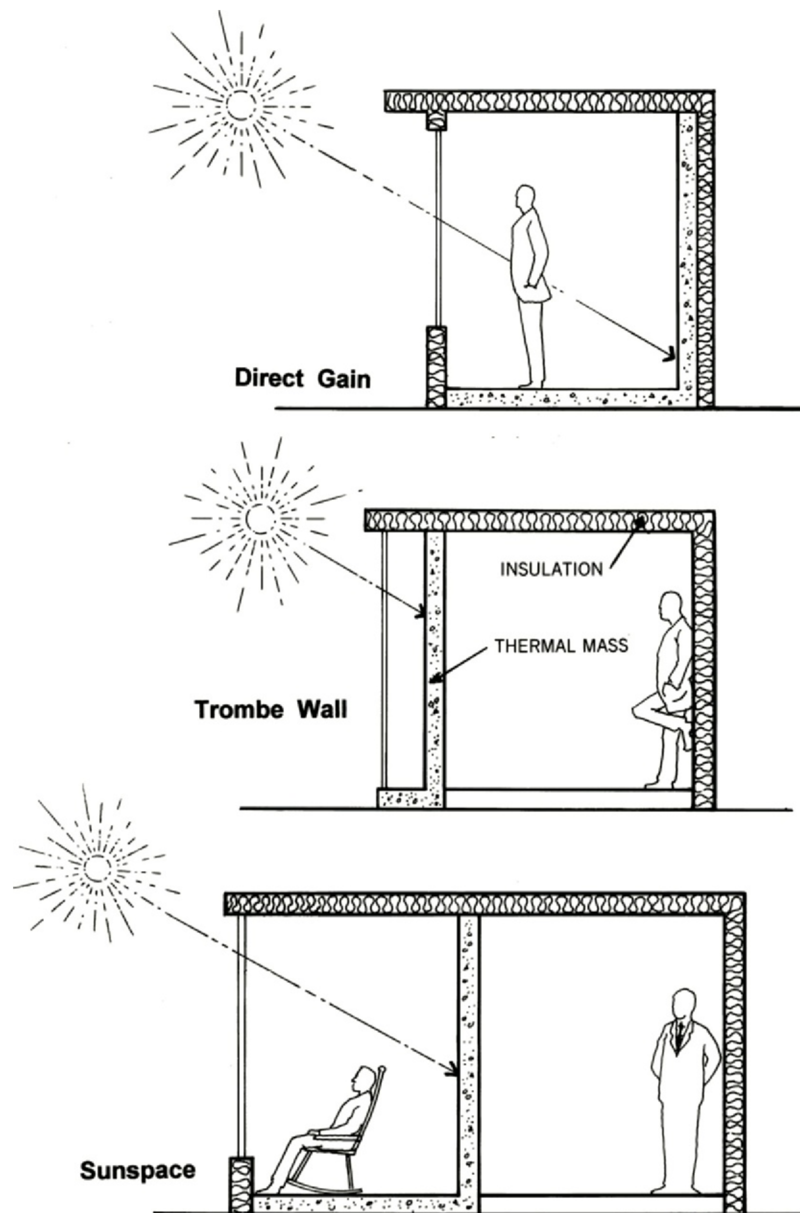


Figure 7.5a The three main types of passive solar space-heating systems are: direct gain, Trombe wall, and sunspace.

Every building with a heating system should use passive solar space heating if there is access to the winter sun!

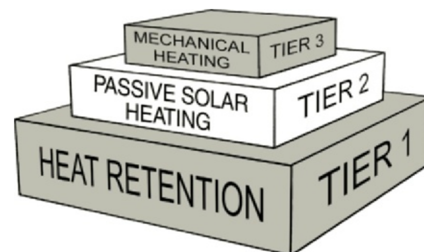


Figure 7.5b Passive solar heating is the second tier of the three-tier approach to sustainable heating. The first tier includes heat retention.

7.6 DIRECT-GAIN SYSTEMS

Every south-facing window creates a direct-gain system, while windows facing east, west, and especially north lose more heat than they gain in the winter. The greenhouse effect, described in Chapter 3, acts as a one-way heat valve. It lets the short-wave solar energy enter but blocks the heat from escaping (Fig. 7.6a). The thermal mass inside the building then absorbs this heat, both to prevent daytime overheating and to store it for nighttime use (Fig. 7.6b). The proper ratio of mass to south-facing glazing is important.

The graph in Figure 7.6c shows the heating effect of south glazing in a building with the conventional mechanical heating system turned off. Curve "A" is the outdoor temperature during a typical cold but sunny day. Curve "B" describes the indoor temperature in a direct-gain system with little mass. Notice the large indoor temperature swing from day to night. In the early afternoon, the temperature is much above the comfort zone, while late at night it is below the comfort zone. Increasing the area of south glazing will not only raise the curve but also increase the temperature swing. The overheating in the afternoon would then be even worse.

In the graph of Figure 7.6d, we see the benefits of thermal mass (curve "A"). Although the outdoor temperature is the same as in Figure 7.6c, the indoor temperature (curve "C") is almost entirely within the comfort zone. The thermal mass has reduced the amplitude of the temperature swing so that little overheating occurs in the afternoon and little overcooling at night. Thus, the designer's goal is to get the right mix of south-glazing area and thermal mass so that the indoor temperature fluctuates within the comfort zone.

The ideal and most convenient location for thermal mass is the floor, because it receives the most direct sunlight, and floor heating is the most comfortable type of heating.

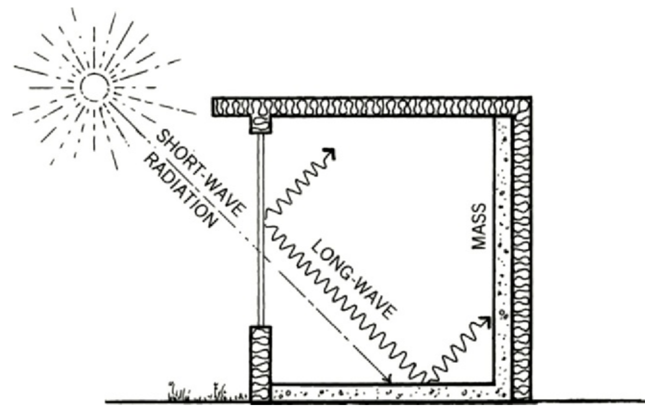


Figure 7.6a The greenhouse effect collects and traps solar radiation during the day.

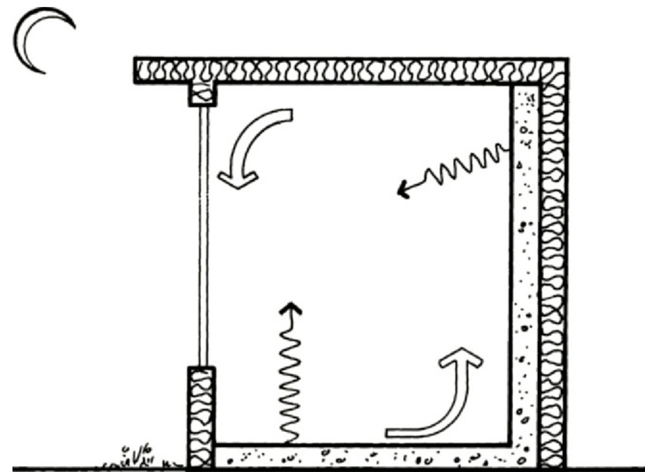


Figure 7.6b The thermal mass stores heat for nighttime use while preventing overheating during the day.

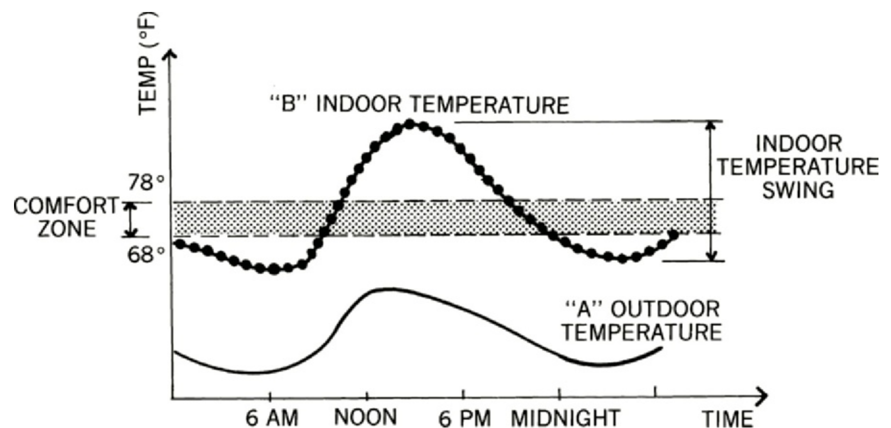


Figure 7.6c A low-mass passive solar building will experience a large indoor temperature swing during a twenty-four-hour period of a winter day. The comfort zone is assumed to be 68° to 78°F (20° to 25°C).

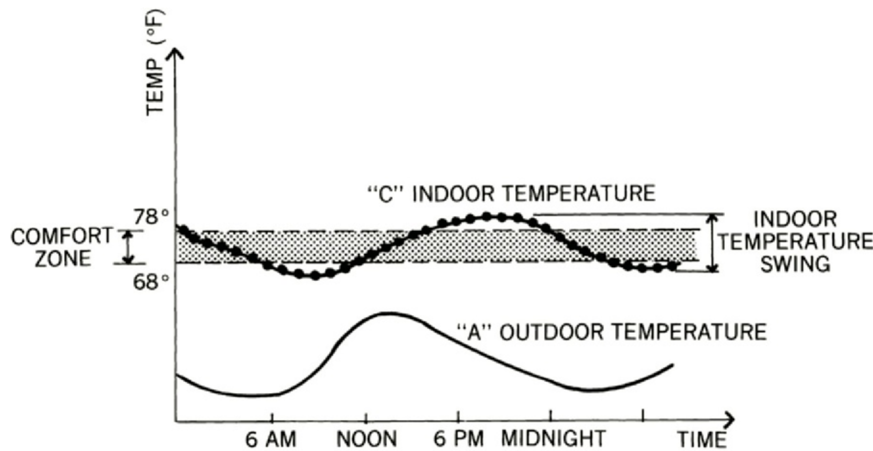


Figure 7.6d A high-mass passive solar building will experience only a small indoor temperature swing during a winter day.

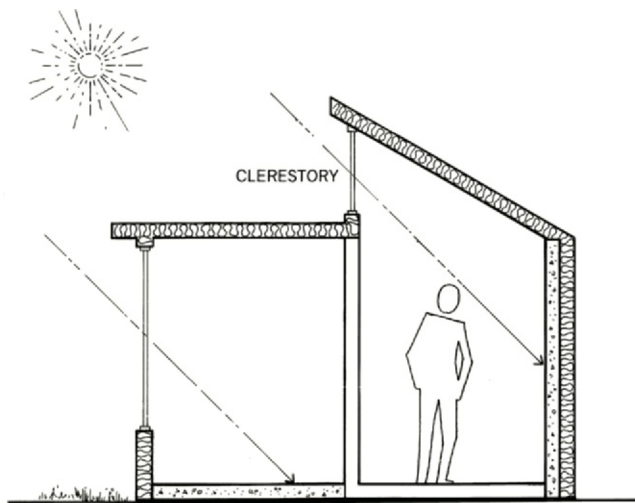


Figure 7.6e Use clerestory windows to bring the solar radiation directly to interior or north-facing rooms.



Figure 7.6f The clerestories of the Smith Middle School in Chapel Hill, North Carolina, provide both passive solar heating and excellent daylighting. The windows have light shelves for additional daylighting.

Thus, in most situations, a concrete floor slab should be used. A modern concrete floor is sustainable, healthy, and beautiful. Rich colors and patterns are possible through the use of colored concrete, stains, or special aggregates near the surface (Colorplate 1). The concrete can also be hardened and polished to create a very durable, smooth finish. Thus, additional floor coverings that could interfere with heat absorption/release and that could produce undesirable volatile organic compounds (VOCs) are unnecessary.

Since in direct gain the building is the collector, all contents, such as the drywall, furniture, and books, act as thermal mass. However, the contents are usually not sufficient to store an adequate amount of heat without additional thermal mass. When there is no concrete floor or when even more thermal mass is desired, it can be provided in the form of masonry walls, water containers, or phase-change materials. These alternatives will be discussed in more detail later in this chapter.

Although solar heat can be supplied by convection to the rooms on the north side of a building, it is much better to supply solar radiation directly by means of south-facing clerestory windows, as shown in Figure 7.6e. Besides bringing warming sunlight further into the building, clerestories also provide excellent daylighting, because light from above is best (Fig. 7.6f).

Frank Lloyd Wright's solar hemicycle, described before, is a good example of the direct-gain approach. Although the Urban Villa shown in Figure 7.6g also has a curved, south-facing wall, most direct-gain systems consist of straight walls facing due south or as close to south as possible. Of all the passive systems, direct gain is the most efficient when energy collection and first costs are the main concerns.



Figure 7.6g The Urban Villa has a large south-facing facade that is 40 percent glass. It minimizes heat loss by using superinsulation, many shared walls, and a compact design. Summer comfort is achieved through ventilation and shading. Even though the building is located at 52° N latitude, the balconies are not sufficient to shade the summer sun, and therefore, exterior roll-down shades are also used at the outer edge of the balconies. (Photograph from CADDET Technical Brochure No. 64)

7.7 DESIGN GUIDELINES FOR DIRECT-GAIN SYSTEMS

Area of South Glazing

Use Table 7.7a as a guideline for initial sizing of south-facing glazing. The table is based on the seventeen climate regions described in Chapter 5. The last column shows how much more effective passive heating systems are when night insulation is used over the windows. Very high R-value windows are usually not a good option for south windows because the solar transmission decreases as the thermal resistance increases. The best solution for south windows is to maximize the solar transmission and use night insulation to reduce the heat loss. The night insulation can also be used in the summer during the day to keep the sun and heat out.

Notes on Table 7.7a

1. The table presents optimum south-glazing areas.

Table 7.7a Rules for Estimating Optimum Areas of South-Facing Glazing for Direct-Gain and Trombe Walls

Climate Region (see Chapter 5)	Reference City	South-Glazing Area as a Percentage of Floor Area*	Heating Load Contributed by Solar (%)	
			No Night Insulation	With Night Insulation
1	Hartford, CT	35	19	64
2	Madison, WI	40	17	74
3	Indianapolis, IN	28	21	60
4	Salt Lake City, UT	26	39	72
5	Ely, NE	23	41	77
6	Medford, OR	24	32	60
7	Fresno, CA	17	46	65
8	Charleston, SC	14	41	59
9	Little Rock, AK	19	38	62
10	Knoxville, TN	18	33	56
11	Phoenix, AZ	12	60	75
12	Midland, TX	18	52	72
13	Fort Worth, TX	17	44	64
14	New Orleans, LA	11	46	61
15	Houston, TX	11	43	59
16	Miami, FL	2	48	54
17	Los Angeles, CA	9	58	72

*Use the floor area of those parts of the building that will receive benefits from solar heating either by direct radiation or by convection from the solar-heated parts of the building.

Table 7.7b Rules for Estimating Required Thermal Mass in Direct-Gain Systems

Thermal Mass	Thickness inches (cm)	Surface Area to Glazing Area Ratio
Masonry or concrete exposed to direct solar radiation (Fig. 7.7b top)	4–6 (10–15)	3
Masonry or concrete exposed to reflected solar radiation (Fig. 7.7b bottom)	2–4 (5–10)	6
Water exposed to direct solar radiation	6–12 (15–30)	About 1/2
Phase change material exposed to direct solar radiation	1–4 (2.4–10)	1

2. Smaller south-glazing areas than those shown in the table will still supply a significant amount of heat.
3. Larger glazing areas will collect more solar energy.
4. Adequate thermal mass must be supplied (see Table 7.7b).
5. Windows should be double-glazed without low-e.
6. The building must be well insulated.
7. Unless large amounts of light are desired for daylighting, sunbathing, etc., direct-gain glazing areas should not exceed about 20 percent of the floor area. In those cases where more than 20 percent glazing is recommended, use either Trombe walls or sunspaces to supply the additional glazing area.



Figure 7.7a Thermal mass can also consist of vertical tubes filled with water. The tubes can be opaque, translucent, or transparent. (Courtesy of and © Solar Components Corporation.)

Thermal-Mass Sizing

Use Table 7.7b as a guideline for sizing thermal mass for direct-gain systems. Keep in mind that slabs and walls of concrete, brick, or rock should be about 4–6 in. (10–15 cm) thick. Because of time lag, most heat in a solid is stored near the surface that is exposed to the sun. Since heat does not travel beyond about 6 inches (15 cm) before the sun sets, only the first 6 inches (15 cm) are useful for heat storage. In water, however, heat is transferred quickly by convection currents. Thus, water containers can be more than 12 inches (30 cm) deep (Fig. 7.7a). Materials that are exposed to neither direct nor reflected sunshine store relatively little heat.

Notes on Table 7.7b

1. A combination of mass directly and indirectly exposed to the sun is quite common.
2. The table specifies minimum mass areas. Additional mass will increase thermal comfort by reducing temperature extremes.
3. Mass surface area is more important than mass thickness.
4. Keep mass as close as possible to the floor for structural as well as thermal reasons.
5. The thermal mass should be medium to dark in color, while surfaces of nonmassive materials should be very light in color to reflect the solar radiation to the darker mass materials (Fig. 7.7b).
6. For more information on thermal mass, see Section 7.17.

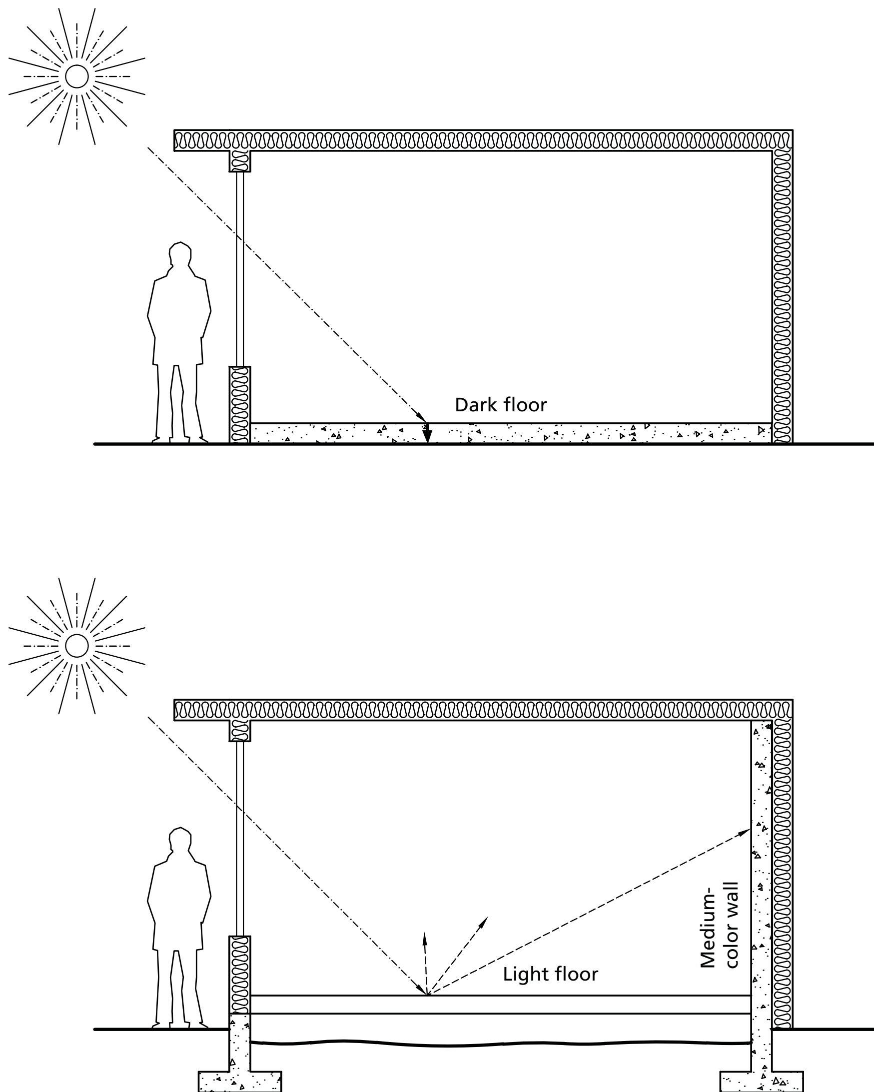


Figure 7.7b Massive floors should be medium to dark in color in order to absorb sunlight (upper section). On the other hand, a lightweight floor should have a light color in order to reflect the sunlight to more massive surfaces (lower section).

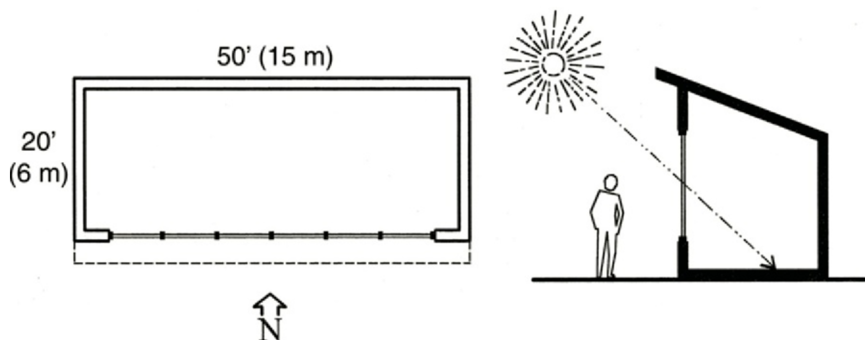


Figure 7.8 The plan and section used in the direct-gain example problem are shown.

7.8 EXAMPLE

Design a direct-gain system for a 1000 ft^2 (90 m^2) building in Little Rock, Arkansas, as shown in Figure 7.8.

Procedure:

1. Table 7.7a tells us that if the area of south-facing glazing is 19 percent of the floor area, then we can expect solar energy to supply about 62 percent of the winter heating load if night insulation is used. Use this recommendation unless there are special reasons to use larger or smaller glazing areas.
2. Thus, the area of south-facing glazing should be about 19 percent × 1000 ft^2 = 190 ft^2 (19 percent × 90 m^2 = 17.1 m^2).
3. Table 7.7b tells us that we will need 3 ft^2 (3 m^2) of mass for each square foot (m^2) of glazing if the mass is directly exposed to the sun. Thus, 190 ft^2 × 3 = 570 ft^2 (17.1 m^2 × 3 = 51.3 m^2) is required. If we use a concrete slab, then we have a slab area of 1000 ft^2 (90 m^2), of which only 570 ft^2 (51.3 m^2) is required for storing heat. The remaining 430 ft^2 (38.7 m^2) will help to reduce the indoor daily temperature swing or it can be covered by carpet if desired.

7.9 TROMBE WALL SYSTEMS

The Trombe (a.k.a. indirect gain) wall was named after Professor Felix Trombe, who developed this technique in France in 1966. In this passive system, the thermal mass consists of a wall just inside the south-facing glazing (Fig. 7.9a). As before, the greenhouse effect traps the solar radiation. Because the surface of the wall facing the sun is either covered with a **selective coating** (see Section 3.11) or painted a dark color, it gets quite hot during the day, causing heat to flow into the wall. Since the Trombe wall is quite thick—often about 12 in. (30 cm)—and the time lag is quite long, the heat does not reach the

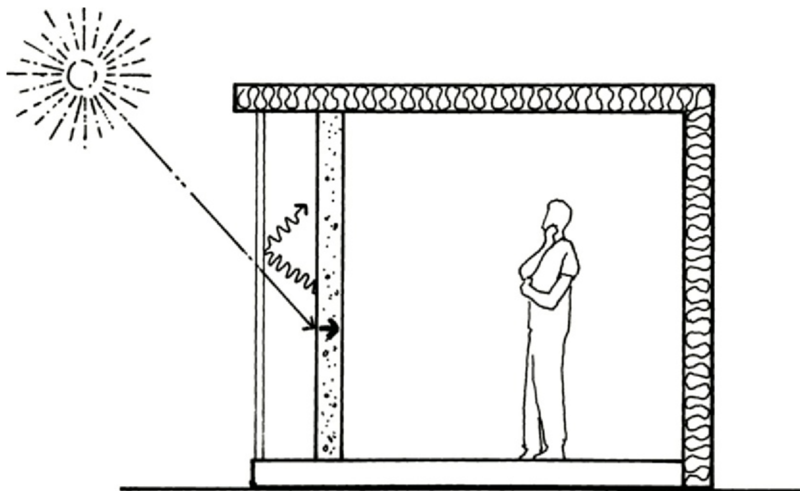


Figure 7.9a The Trombe wall passive-solar heating system collects heat without having light enter the space.

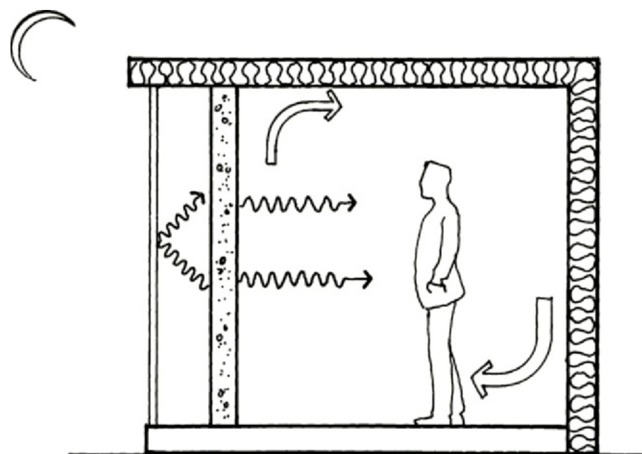


Figure 7.9b Because of the wall's eight- to twelve-hour time lag, most of the heat is released at night.

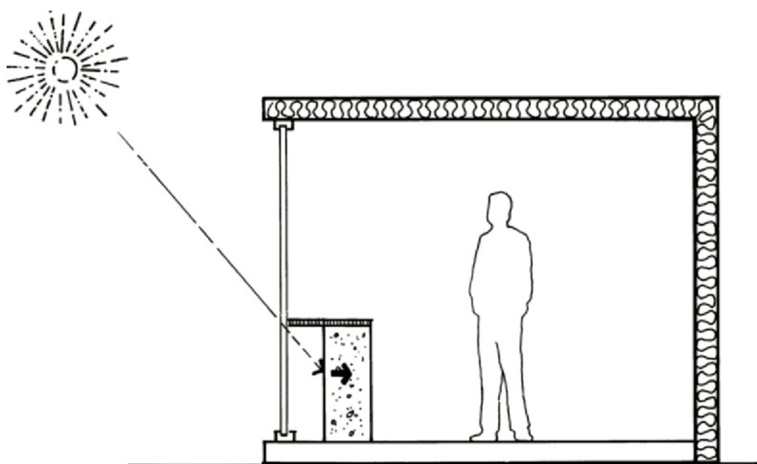


Figure 7.9c A half-height wall allows controlled direct gain for daytime heating and daylighting while also storing heat for the night. Water tanks or tubes could be used instead of concrete or masonry.

interior surface until evening. This time-lag effect of mass was explained in Section 3.18. If there is enough mass, the wall can act as a radiant heater all night long (Fig. 7.9b).

When only the sun's heat and not its light are desired, the Trombe wall is the system of choice. Because this is a rare occurrence, the Trombe wall is ordinarily used in combination with direct gain. The direct-gain part of the system delivers heat early in the day, functional light, views, and the delight of winter sunshine, while the Trombe wall stores heat for nighttime use. The combination of systems prevents the need for excessive light levels, which can cause glare and fading of colors. When one carefully chooses the right combination of systems, great thermal and visual comfort is possible.

Although the Trombe wall is usually made of solid materials, such as concrete, brick, stone, or adobe, it can also be made of containers of water. Rectangular steel tanks can be fabricated, but most water walls consist of vertical tubes. If steel tubes or tanks are used, they should be painted a dark color on the glazing side and any color on the room side. Corrosion of the steel tanks can be prevented by adding either rust control additives or sacrificial metal to the water.

As mentioned before, a mix of Trombe walls and direct gain usually yields the best design solution. Although many Trombe walls are full height with punched windows, some are built as a parapet wall (Fig. 7.9c and 7.9d). An arrangement, as shown in Figure 7.16b, can increase morning pickup, prevent afternoon overheating, and provide storage for the night.

The Visitor Center at Zion National Park, Utah, uses many passive strategies. South-facing windows provide both daylight and winter heating. The wall below the windows is a Trombe wall characterized by the use of textured glazing (Fig. 7.9e). The windows and Trombe walls are shaded in the summer, and "cool towers" supply cool air, as described in Section 10.13.

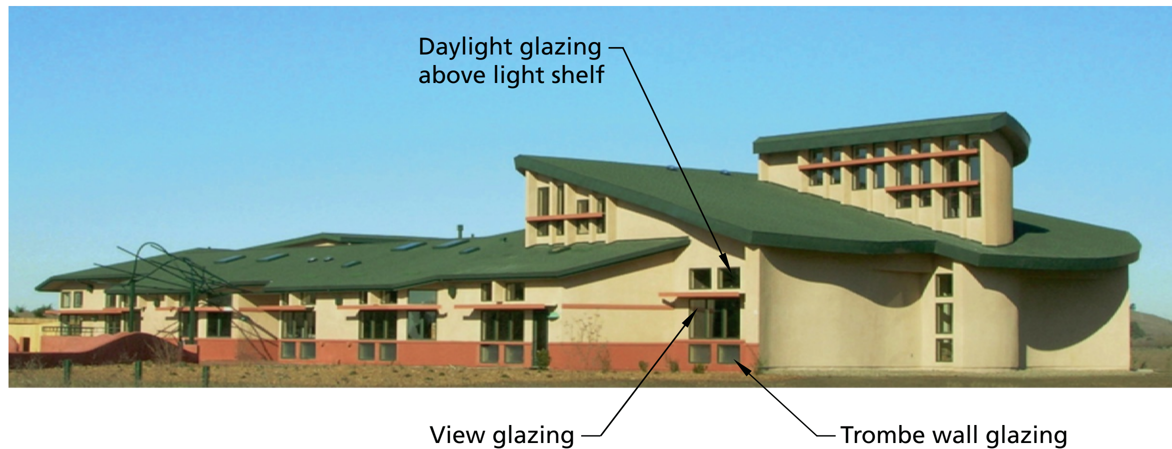


Figure 7.9d This synagogue uses many passive strategies including the underwindow Trombe walls. Note the ground level windows with three types of glazing: Trombe wall, view, and daylighting. Water tanks are used instead of concrete, which is shown in Fig. 7.9c. From *Passive Solar Architecture*, by David Bainbridge and Ken Haggard, Chelsea Green, White River Jct., Vermont, 2011. Photo by Ken Haggard.



Figure 7.9e The Visitor Center at Zion National Park uses both Trombe walls and direct-gain passive solar heating. The clerestory windows provide high-quality daylighting and direct gain for the north end of the building. Also note the photovoltaic panels on the south-facing roof.



Figure 7.9f The Shelly Ridge Girl Scout Center near Philadelphia, Pennsylvania, utilizes both direct-gain and Trombe wall passive systems. Glass is used for the direct gain, and translucent Fiberglas panels are used for the Trombe wall. Awnings are extended in the summer to shade the direct-gain windows.

The Shelly Ridge Girl Scout Center near Philadelphia, Pennsylvania, is another wonderful example of mixed Trombe wall and direct-gain systems (Fig. 7.9f). Since most scout activities happen during the day and early evening, the Trombe wall was made of brick only 4 in. (10 cm) thick so that the resulting short time lag delivered the heat during the afternoon and early evening. There was plenty of direct gain for early heating and daylighting (Fig. 7.9g). Because the 4 in. (10 cm) thick Trombe wall was much too high to be stable, a timber grid was used to support the brick and the glazing (Fig. 7.9h). Crank-out awnings were extended in the summer to shade most of the direct-gain windows.

Summer evenings, however, would be cooler if the Trombe wall were also shaded. A shade screen hung in front of the glazing during the summer would be especially effective since it would shade the Trombe wall from direct, diffuse, and reflected radiation (Fig. 7.9i).

A roll-down radiant barrier (see Section 15.6) should be included in the space between the glass and mass wall to reduce nighttime heat losses. That radiant barrier will also reduce summer daytime heat gain. However, using both an outdoor shade and an indoor radiant barrier would be best.



Figure 7.9g The direct-gain windows provide daylighting, views, and heat early in the day, while the Trombe wall provides heat in the early evening.

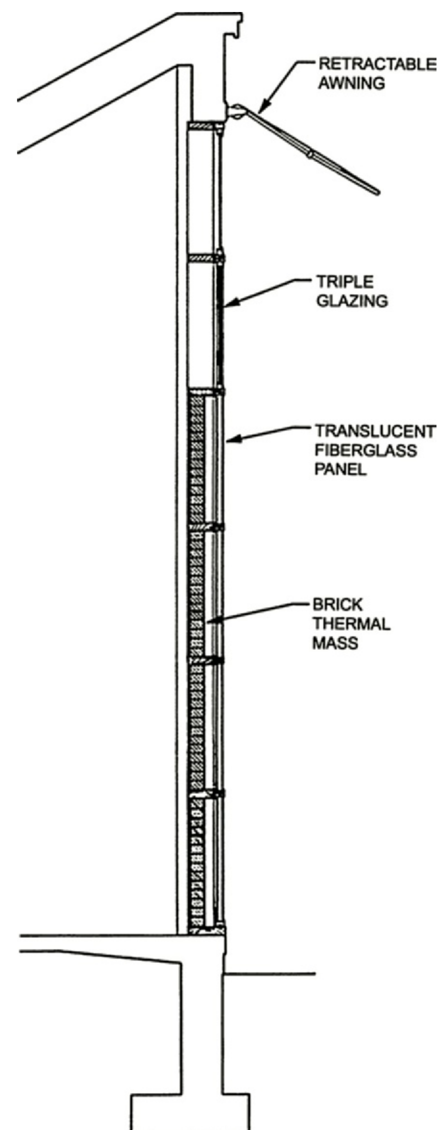


Figure 7.9h Because of the slenderness of this Trombe wall, a wooden frame was used to support both the brick and the window walls. (Courtesy of Bohlin Cywinski Jackson Architects.)

The Girl Scouts learned the methods and benefits of passive solar firsthand from using the building. They learned more experiential lessons from the direct-gain heated lobby (Area #4 in Fig. 7.9j), where a stained-glass gnomon and hour marks embedded in the floor create a sundial.

Some early Trombe walls had indoor vents to supply daytime heat in winter and outdoor vents to prevent summer overheating. In most cases, the vents are an unnecessary complication. Instead, direct gain should supply daytime heat in the winter, and an outdoor shading device should prevent heat collection in the summer.

From the outside, Trombe walls are sometimes indistinguishable from windows. Under certain lighting conditions, however, the dark wall is visible. If this is undesirable, textured or diffusing glass can be used both to hide the dark wall and to serve as an aesthetic device to differentiate the Trombe wall from ordinary windows. Since dark colors are almost as effective as black, some Trombe walls use clear glass to show the dark brick, dark natural stones, water tubes, or another attractive thermal-mass system.

The Trombe wall system is also known as the thermal-storage wall system. This author prefers the term "Trombe wall" because not all thermal walls are part of this system—only those that are just inside and parallel to the glazing. Trombe walls are also known as indirect gain systems which is descriptive but not memorable.

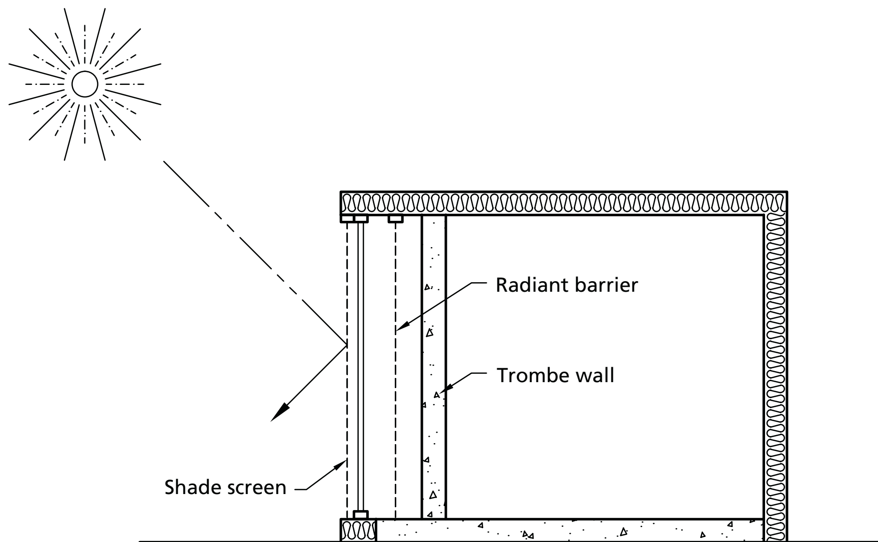


Figure 7.9i In hot climates, a shade screen should be draped over the Trombe wall glazing during the summer. Also a radiant barrier should be in place during winter nights and summer days.

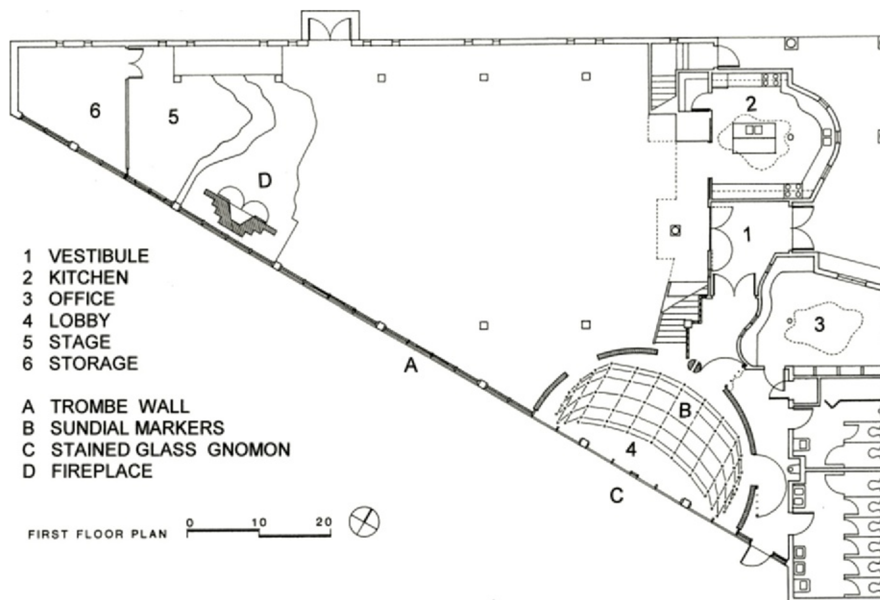


Figure 7.9j In the lobby (area 4) a stained-glass gnomon projects the time and date in the room-size sundial embedded in the floor slab. The triangular shape of the buildings makes the south wall the largest of the three walls. (Courtesy of Bohlin Cywinski Jackson Architects.)

Table 7.10 Rules for Estimating the Required Thickness of a Trombe Wall

Thermal Mass	Thickness, in inches (cm)*	Surface Area to Glazing Area Ratio
Adobe (dry earth)	6–10 (15–25)	1
Concrete or brick	10–16 (25–40)	1
Water†	8 or more (20)	1

*Use the thinner thickness for evening heat and the thicker one for all-night heat.
†If tubes are used, they should be at least 10 in. (25 cm) in diameter.
Source: Solar Age, May 1979, p. 64.

7.10 DESIGN GUIDELINES FOR TROMBE WALL SYSTEMS

Area of South Glazing

Table 7.7a is used for Trombe walls as well as direct-gain systems. The total area of south glazing can be divided between the two systems as the designer wishes.

Thermal-Mass Sizing

The area of south-facing glazing should be matched by an equal area of thermal mass. However, the mass must be much thicker than that in direct-gain systems. The thickness for various materials is shown in Table 7.10. For best results, the mass should be at least 3 in. (7.5 cm) from the glazing to allow cleaning and the insertion of a radiant barrier. The surface facing the glazing should be covered with a black high-efficiency "selective" coating if possible, while the surface facing the living space can be any color, including white. If a selective coating is not used, a removable radiant barrier becomes especially important.

7.11 EXAMPLE

Redesign the building in Example 7.8 to be half Trombe wall and half direct gain.

Procedure:

1. Total recommended south-facing glazing is again obtained from Table 7.7a: 19 percent × 1000 ft^2 = 190 ft^2 (19 percent × 90 m^2 = 17.1 m^2).
2. Since half of the glazing will be for direct gain, the Trombe wall will require 50 percent × 190 ft^2 = 95 ft^2 (0.5 × 17.1 m^2 = 8.6 m^2).
3. If we use a brick Trombe wall, it will have an area of 95 ft^2 (8.6 m^2) and a thickness of at least 10 in. (25 cm) (from Table 7.10). The slab for direct gain will have an area of 95 ft^2 × 3 = 285 ft^2 (8.6 m^2 × 3 = 25.8 m^2) (Table 7.7b).

4. Consider using a Trombe wall 3 ft high (0.9 m) × 32 ft long (9.6 m) = 96 ft^2 > 95 ft^2 required (0.9 m × 9.6 m = 8.6 m^2) as shown in Figure 7.9c. Do not block the inside of the Trombe wall with furniture since it must act as a radiator at night.
5. The window above the wall would also be 3 ft high (0.9 m) × 32 ft (9.6 m) long = 96 ft^2 > 95 ft^2 required for the direct gain glazing (0.9 m × 9.6 m = 8.6 m^2).

7.12 SUNSPACES

Sunspaces, also known as remote gain passive solar systems, are designed to collect heat for the main part of a building, as well as to serve as a secondary living area. This concept is derived from the conservatories popular in the eighteenth and nineteenth centuries.

Until recently, this design element was usually called an "attached greenhouse," but that was a misleading name because growing plants is only an optional function. More appropriate terms were "solarium" or "sunroom," but the term sunspace seems to have become most common. Sunspaces are one of the most popular passive systems, not because of their heating efficiency but because of the amenities that they offer. Most people find the semi-outdoor aspect of sunspaces extremely attractive. Almost everyone finds it pleasurable to be in a warm, sunny space on a cold winter day.

Sunspaces are considered adjunct living spaces because the temperature is allowed to swing widely. On a sunny, cold day, the temperature can go as high as 90°F (32°C) during the day and cool down to 50°F (10°C) just before sunrise. A sunspace is a solar collector that can also be used as an attractive living space much, but not all, of the time. Consequently, a sunspace must be designed as a separate thermal zone that can be isolated from the rest of the building. Figure 7.12a shows the three ways a sunspace can relate physically to the main building.

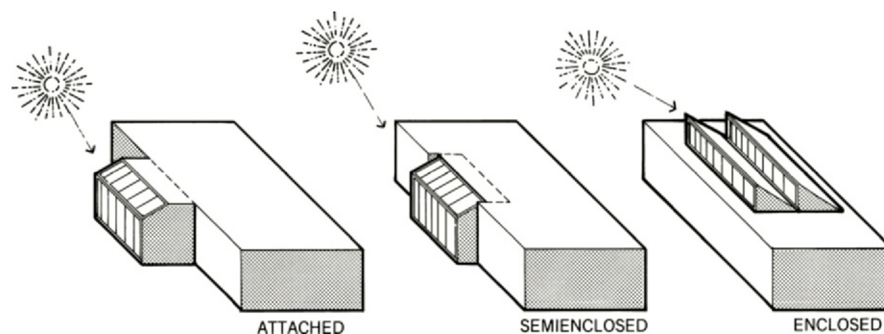


Figure 7.12a Possible relationships of a sunspace to the main building.

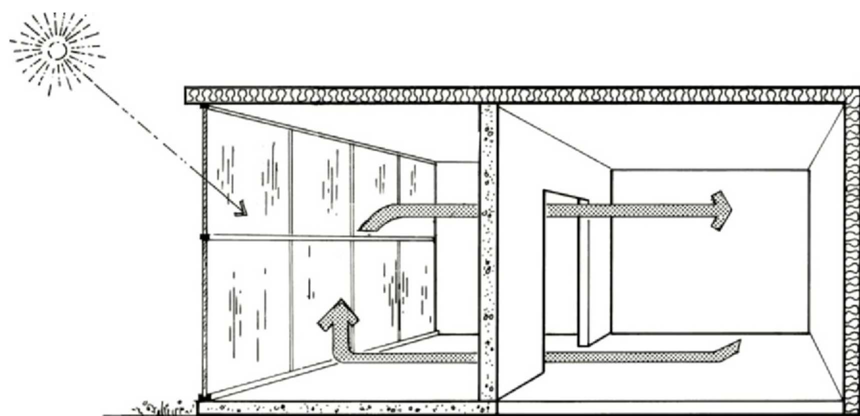


Figure 7.12b During the day, the sunspace collects solar radiation and distributes much of the heat to the rest of the building. Thermal mass stores the heat for nighttime use.

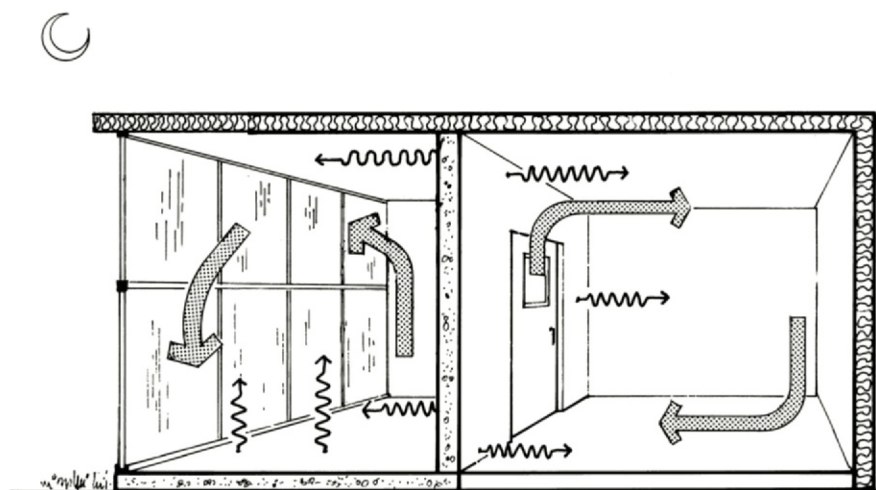


Figure 7.12c At night, the sunspace must be sealed from the main building to keep it from becoming an energy drain on the main building.

In Figure 7.12b we see a sunspace collecting solar heat during the day. Much of the heat is carried into the main building through doors, windows, or vents. The rest of the captured solar heat is absorbed in the sunspace's thermal mass such as the floor slab and the masonry common wall. At night, as seen in Figure 7.12c, the doors, windows, and vents are closed to keep the main part of the building warm. The heat stored in the thermal

mass keeps the house comfortable and prevents the sunspace from freezing.

Because sunspaces are generally poorly insulated and shaded, they should not be heated or cooled. Mechanical heating and cooling would require so much energy that a sunspace would become a net loser rather than a gainer of energy. Large temperature swings should be expected, and when the temperatures get extreme, the space should be temporarily abandoned. However, a well-designed sunspace is a delight most of the year.

Because sunspaces not only collect heat during the day but also act as a buffer at night, they are used in the BedZED zero-energy development (Fig. 7.12d). The cross section of the buildings was designed to maximize the south orientation and to prevent the shading of the next row of houses to the north (Fig. 7.12e). Since work areas need less heat than homes, office spaces are placed on the north side of each building. The dynamic roof ventilators (wind cowls) are explained in Section 10.6.



Figure 7.12d The Beddington Zero (fossil) Energy Development (BedZED) uses sunspaces to collect heat during the day, act as a buffer at night, and serve as an additional living space most of the time. Architect Bill Dunster, Engineers: ARUP. (Courtesy of ARUP.)

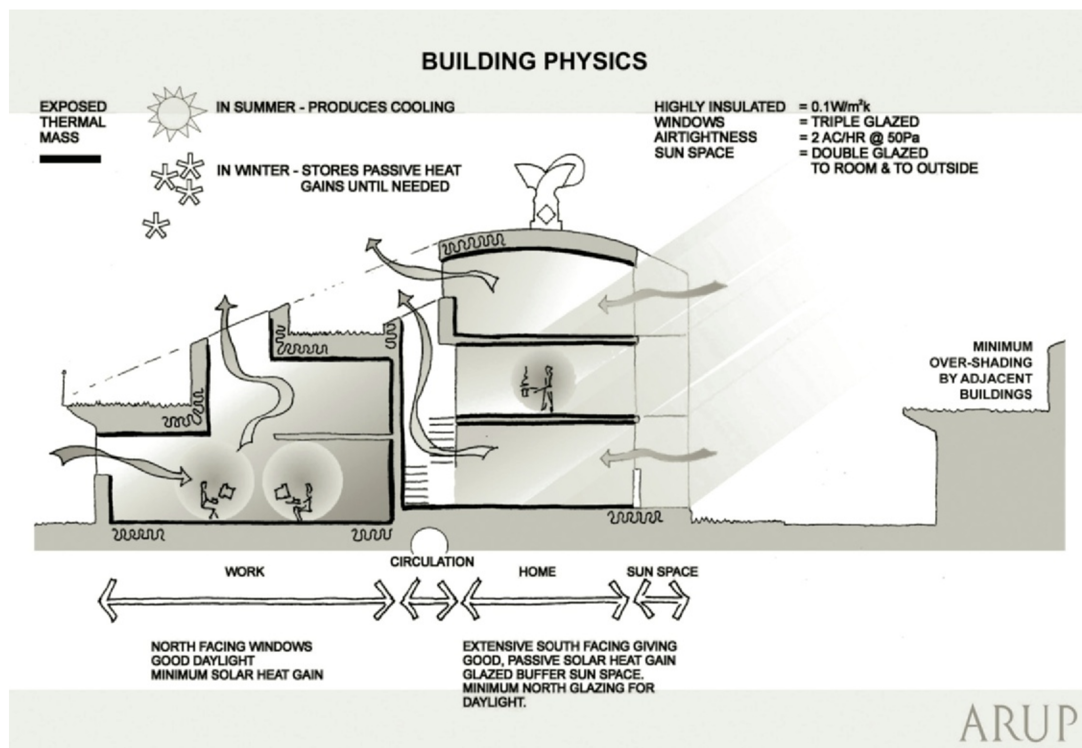


Figure 7.12e This section of BedZED shows the passive solar sunspaces on the south side (to the right) and the cooler work spaces on the north. The shape of the cross section maximizes south exposure for each building while providing solar access to the building to the north. (Courtesy of ARUP.)

7.13 BALCOMB HOUSE

One of the best-known sunspace houses (Fig. 7.13a) belonged to J. Douglas Balcomb, the foremost researcher in passive solar systems. Because it is located in historic Santa Fe, New Mexico, adobe is used for the common wall (Fig. 7.13b). Double doors enable convection currents to heat the house during the day but seal off the sunspace at night (Fig. 7.13c). Also, at night the common adobe wall heats both the house and the sunspace. The sunspace not only contributes about 90 percent of the heating, but it is a delightful place to be much of the time.

Another solar heating strategy used here actually makes this a hybrid solar building. It is partly active solar because fans force the hot air, collecting at the ceiling of the sunspace, to pass through a rock bed below the first-floor slab. This strategy does not contribute much heat, but it does increase the comfort level within the building. Rock beds are rarely used now because of their complexity and expense.

On the roof is a large vent to allow hot air to escape during the overheated periods of summer and fall (Fig. 7.13b). Unfortunately, venting is usually not enough to prevent overheating, and shading of the glass is of critical importance. Since shading inclined glass is much more complicated than shading vertical glass, sloped glazing is not recommended.

The graph in Figure 7.13d illustrates the performance of the Balcomb House during three winter days. It clearly shows the different character of the two thermal zones. Although the addition of a small amount of auxiliary heating can create complete comfort in the house, the sunspace is always allowed its large temperature swing.



Figure 7.13a One of the first and most interesting sunspace houses is the Balcomb residence in Santa Fe, New Mexico.

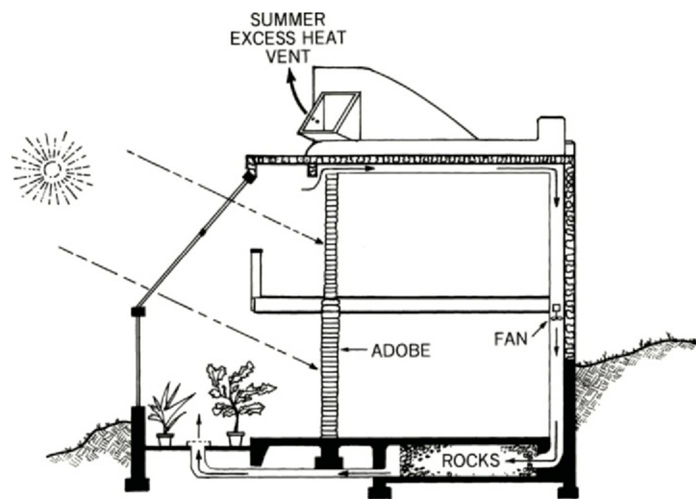


Figure 7.13b A section through the Balcomb House shows the adobe common wall used for storing heat. The sloping south glazing is a problem in the summer and is, therefore, not recommended.

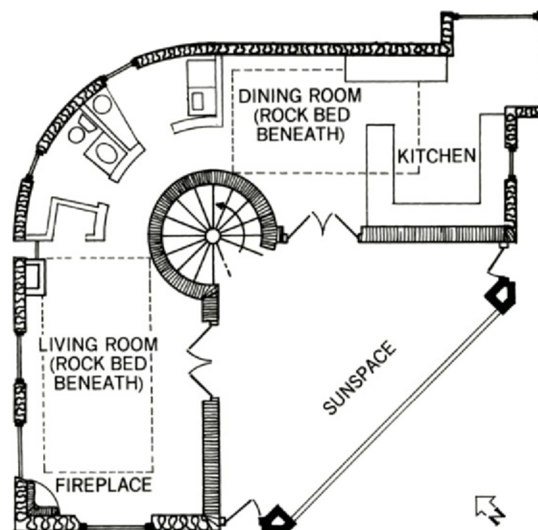


Figure 7.13c This plan of the Balcomb House shows how the building surrounds the sunspace.

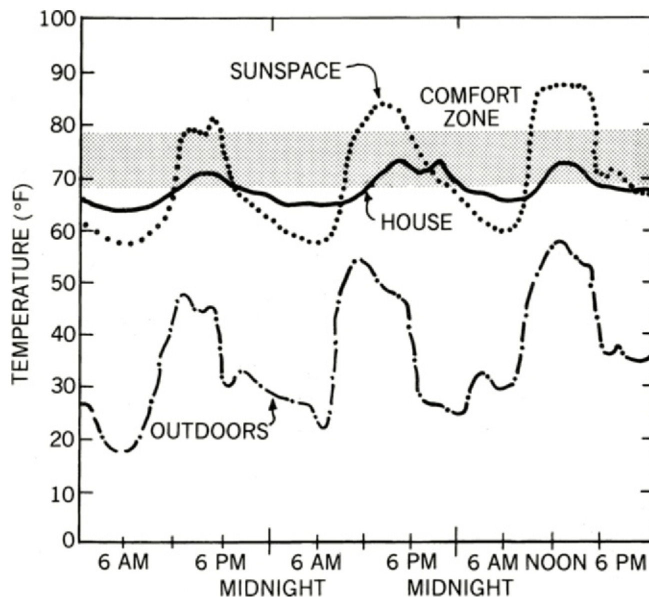


Figure 7.13d The performance of both the house and sunspace are shown for three sunny but cold winter days. Even though no auxiliary heating was used during this test, both the house and sunspace temperatures were almost in the comfort zone. As expected, the sunspace temperatures varied much more than the house temperatures. Passive houses are resilient because they are livable even when conventional heating is lost.

7.14 SUNSPACE DESIGN GUIDELINES

Glazing

To maximize solar heating, the slope of the glazing should be perpendicular to the sun during the coldest time of the year (e.g., January/February). However, from the point of view of safety, water leakage, and, most important, sun shading, vertical glazing is best. Very little if any glazing should be used on the end walls facing east and west. Such glazing is a thermal liability both winter and summer.

Vent Sizing

Because the entire south facade of a sunspace is usually glass, both shading and outdoor venting should be used to prevent severe overheating in the summer. The best venting is achieved by having both high and low openings to maximize the stack effect. Both the inlet and outlet vents should be at least 8 percent of the glazing area in size (i.e., total vent area equals 16 percent). A smaller inlet vent can be used if a fan is used to exhaust the hot air high in the sunspace.

To heat the house in the winter, the indoor openings in the form of doors, windows, vents, or fans are required in the common wall between the house and the sunspace. The total area of any combination of these openings must add up to a minimum of 16 percent of the glazing area. Larger openings are better.

Thermal-Mass Sizing

The size of the mass depends on the function of the sunspace. If it is primarily a solar collector, then there should be little mass so that most of the heat ends up in the house. On the other hand, if the sunspace is to be a space with a more modest temperature swing, it should have much more mass.

A good solution for temperate climates is a common thermal-storage wall, as shown in Figure 7.14a. In extremely hot or cold climates, it might be desirable to completely isolate the house from the sunspace. In this case, an insulated, less massive masonry wall might be used as shown in Figure 7.14b. On a sunny winter day, the doors, windows, or vents in the common wall are opened. When the sunspace needs to be isolated from the main building, the openings are closed and the insulated wall acts as a thermal barrier. With either type of wall, water or a phase-change material can be efficiently used instead of masonry for thermal storage. For rules in sizing the mass in a sunspace, see Table 7.14.

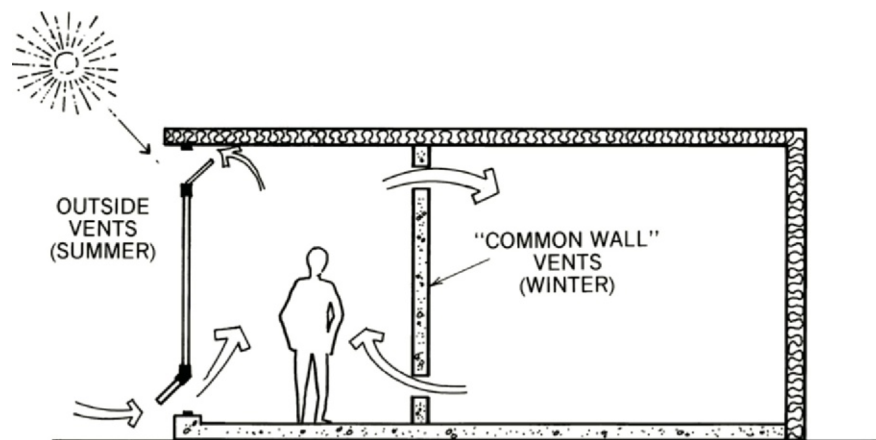


Figure 7.14a To prevent overheating in the summer, the sunspace must be vented to the outdoors. Vents, windows, or doors in the common wall allow daytime winter heat to flow from the sunspace into the main building.

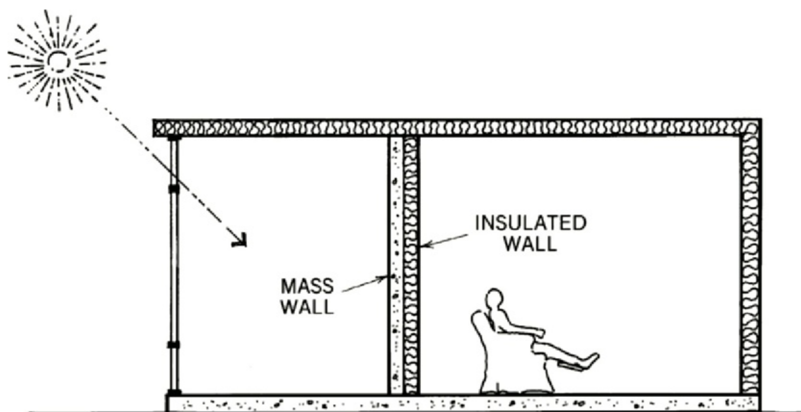


Figure 7.14b In extreme climates, the sunspace should be completely isolated from the main building by an insulated wall.

Table 7.14 Rules for Estimating the Required Thermal Mass in Sunspace Systems

Thermal Mass	Thickness in Inches (cm)	Surface Area to Glazing Area Ratio
Masonry common wall (noninsulated)	8–12 (20–30)	1
Masonry common wall (insulated)*	4–6 (10–15)	2
Water†	About 12	About 1/2

*Since this mass is exclusively for the sunspace, some additional mass will be required for the main building.
†Use about 2 gallons of water for each square foot (90 L/m^2) of glazing.
Source: Solar Age, June 1984, p. 32.

7.15 COMPARISON OF THE THREE MAIN PASSIVE HEATING SYSTEMS

Table 7.15 compares the three main passive solar heating systems by listing the main advantages and disadvantages of each approach. Figure 7.15 shows the logic that can be used to design a passive solar space heating system.

7.16 GENERAL CONSIDERATIONS FOR PASSIVE SOLAR SYSTEMS

The following comments refer to all passive systems.

Orientation

"Orientation is 80 percent of passive solar design," says Doug Balcomb, the foremost passive solar scientist. Usually solar glazing should be oriented to the south. In most cases, this orientation gives the best results for both winter heating and summer shading. The graph in Figure 7.16a illustrates how the solar radiation transmitted

Table 7.15 Comparison of Passive Solar Heating Systems

	Advantages	Disadvantages
Direct gain	Promotes the use of large picture windows Least expensive Most efficient Can effectively use clerestories Daylighting and heating can be combined, which makes this system very appropriate for schools, small offices, etc.	Possibly too much light, which can cause glare and fading of colors. Concrete floor slabs must not be covered by carpets Overheating can occur if precautions are not taken Fairly large temperature swings must be tolerated (about 10°F [6°C])
Trombe wall	Gives high level of thermal comfort Good in conjunction with direct gain to limit lighting levels Medium cost Good for large heating loads	More expensive than direct gain Less glazing will be available for views and daylighting No wall hangings or other coverings permitted on Trombe wall
Sunspaces	Very attractive amenity Extra living space Can function as a greenhouse	Most expensive system Least efficient Cannot be occupied when too hot or cold

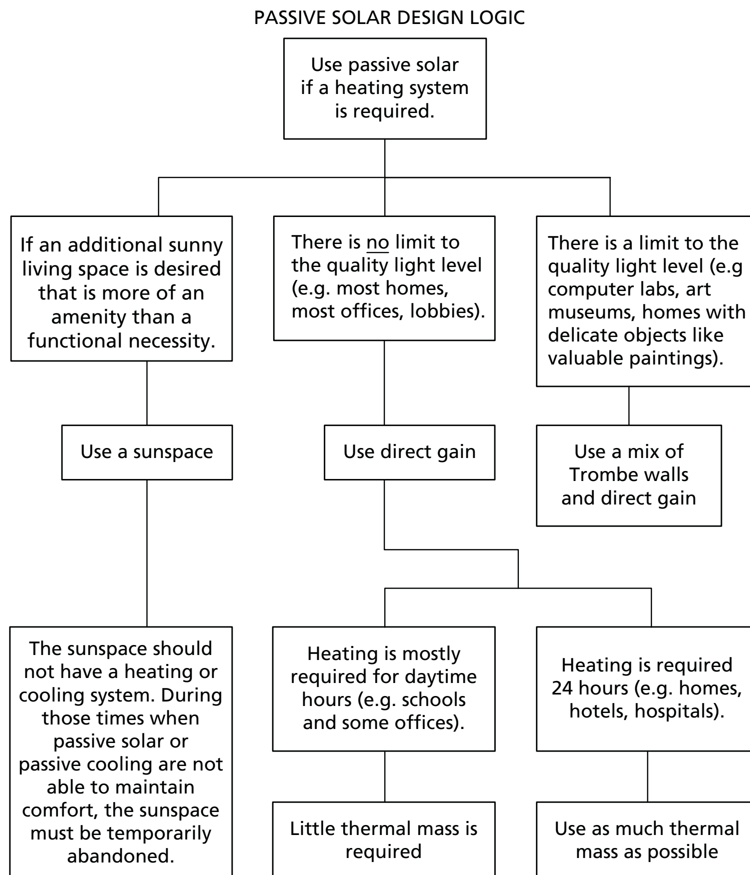


Figure 7.15 This flow chart helps in choosing and designing a passive solar system. It assumes that the sunlight entering is controlled so that it is of high quality (i.e. no glare, no inappropriate sun puddles, etc.).

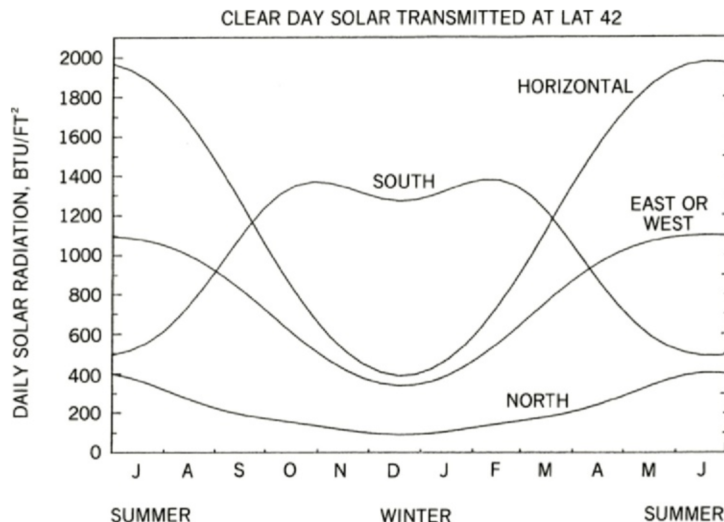


Figure 7.16a Vertical south glazing is usually the best choice because it transmits the maximum solar radiation in the winter and the minimum in the summer. (From *Workbook for Workshop on Advanced Passive Solar Design*, by J. Douglas Balcomb and Robert Jones, © J. Douglas Balcomb, 1987.)

through a vertical south window is maximal in the winter and minimal in the summer. This ideal situation is not true for any other orientation. Note how the curves for horizontal, east–west, and north windows indicate minimal heat collection in the winter and maximal heat collection in the summer. Who would want that? The south orientation is not just better—it is significantly better. In winter, south glazing collects about three times the solar radiation that east or west glazing collects, and in summer, south glazing collects only about one-third the radiation that east or west collects. With shading, the benefits of south glazing are even better. The diagram in Figure 7.16a is for 42° N latitude but the logic is valid from at least 32° to 52°.

Since in the real world a due-south orientation is not always possible, it is useful to know that solar glazing will still work well if oriented up to 20° east or west of true south. Even at 45° to true south, passive solar still works fairly well.

There are special conditions, however, when true south is not best. Consider the following examples:

1. Schools, which need heating early in the morning and little heating in late afternoon or at night, should be oriented about 30° to the east.
2. It is sometimes desirable, as in schools that have night classes, to use a combination of systems, each of which has a different orientation. For example, the solution shown in Figure 7.16b will give quick heating by direct gain in the morning. In the afternoon, overheating is prevented by having the solar radiation charge the Trombe walls for evening use.
3. Areas with morning fog or cloudiness should be oriented west of south.

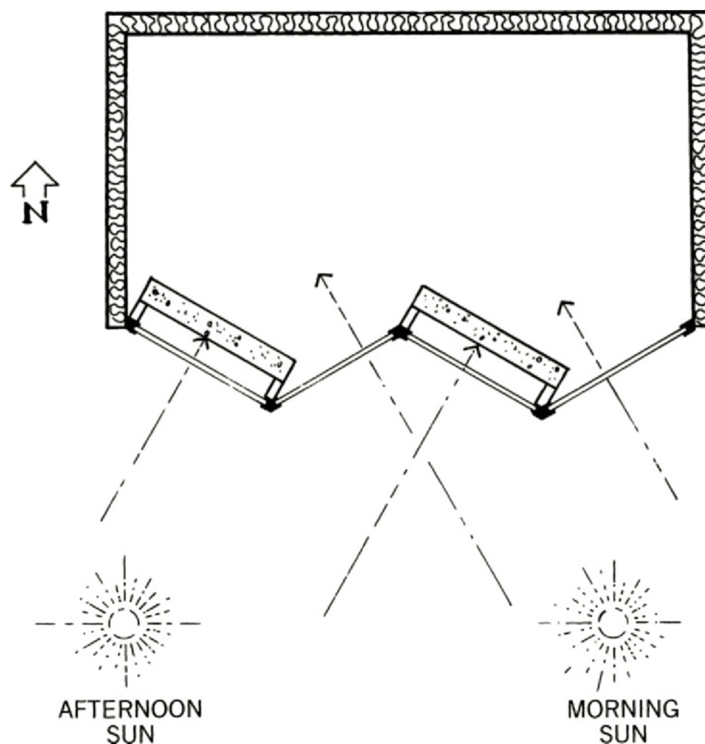


Figure 7.16b Plan view of a combined system of direct gain and Trombe walls to get quick morning heating, prevent afternoon overheating, and provide heating in the evening.



Figure 7.16c Avoid building projections on the south wall that would cause self-shading of south windows in the winter. Many of these windows are shaded on winter afternoons.

4. Buildings that are used mainly at night (e.g., some residences where no one is home during the day) should be oriented about 20° west of south.
5. To avoid shading from neighboring buildings, trees, etc., reorient either to the east or west as needed.

Plan

The plan should be designed to take advantage of the daily cycle of the sun (See Chapter 15, Fig. 15.5f and 15.5g). Waking up to the morning sun and eating breakfast on a table flooded with sunlight on the east side of a house is both physiologically and psychologically satisfying. Later in the day, relaxing in a sun-filled living or family room on the south or southwest side of the building is a great pleasure. There is growing scientific evidence that supporting our natural circadian rhythms can promote well-being.

Avoid plans that have projections toward the south because they shade part of the south facade (Fig. 7.16c). Even if the building is not oriented to the south, a sawtooth wall can allow parts to be oriented correctly (Fig. 7.16d). Use clerestories to bring a southern exposure to northern rooms (see again Fig. 7.6e and f).

Slope of Glazing

To maximize solar collection, many early passive solar systems used south-facing windows inclined so that the glazing was perpendicular to the low winter sun. However, vertical south-facing glazing is almost always the best solution, because it is less expensive, safer, much easier to shade, easier to fit with night insulation, actually collects more heat where reflective snow is common, and has the best year-round performance.

Shading

Passive solar heating systems can become a liability during the overheated periods of the year if they are not properly shaded. Figure 7.16e shows a passively heated building that is well shaded in the summer. Not only should direct sunrays be rejected, but reflected and diffuse radiation should be blocked. The problem of reflected heat is most acute in hot and dry areas, while that of diffuse radiation is most critical in humid regions.

As Chapter 9 will show, any fixed south-facing overhang that is deep enough to fully shade a window for the whole overheated period will also shade the window too much during the underheated period. Consequently, movable overhangs such as awnings should be used. When that is not possible, as in



Figure 7.16d Because of topography the Blue Ridge Parkway Visitor Center could not have a wall facing south even though passive solar heating was desired. A sawtooth arrangement allowed much of one wall to face south for a Trombe wall system and the rest to collect morning direct gain and light. The vents are on the Trombe wall edge.



Figure 7.16e To prevent passive solar from becoming a liability in the summer, the Real Goods Solar Living Center shades the large area of glazing with a combination of roof overhangs, an extensive deciduous plant-covered pergola, and movable awnings, which are not visible in this photograph. (Courtesy of van der Ryn Architects, ©Richard Barnes, photographer.)

south-facing porches or balconies, the glazing line should be moved instead (Fig. 7.16f). A full discussion of shading is presented in Chapter 9.

Reflectors

Exterior specular (mirror-like) reflectors can increase the solar collection without some of the drawbacks of using larger glazing areas. Both winter heat loss and summer heat gain can be minimized by using reflectors rather than larger window sizes to increase the solar collection. Specular reflectors can also be beneficial in daylighting designs, which are discussed in Chapter 13. However, specular reflectors are not inexpensive, and they are quite inefficient when used on narrow windows (Fig. 7.16g).

Since a specular surface reflects light so that the angle of incidence equals the angle of reflectance, the length of the reflector is determined by the ray of sunshine that just clears the head of the window (Fig. 7.16h). For the angle of incidence, use the altitude angle of the sun on January 21 at 12 noon. This angle can be found in Appendix C for any latitude.

To prevent unwanted collection, the specular reflector should be removed or rotated out of the way in the summer. In the case of the Trombe wall below the windows, the reflector can also act as the shading device in the summer (Fig. 7.16i).

Conservation

Night insulation over the solar glazing is highly recommended in most parts of the country, because it can significantly improve the performance of passive solar systems. Night insulation can also be used to reject the sun during summer days. Furthermore, it can offer privacy and eliminate the "black hole" effect of bare glazing at night. Night insulation is most appropriate for direct-gain systems, but it is also recommended for Trombe walls. It is least appropriate for sunspaces since they are allowed a large temperature swing.

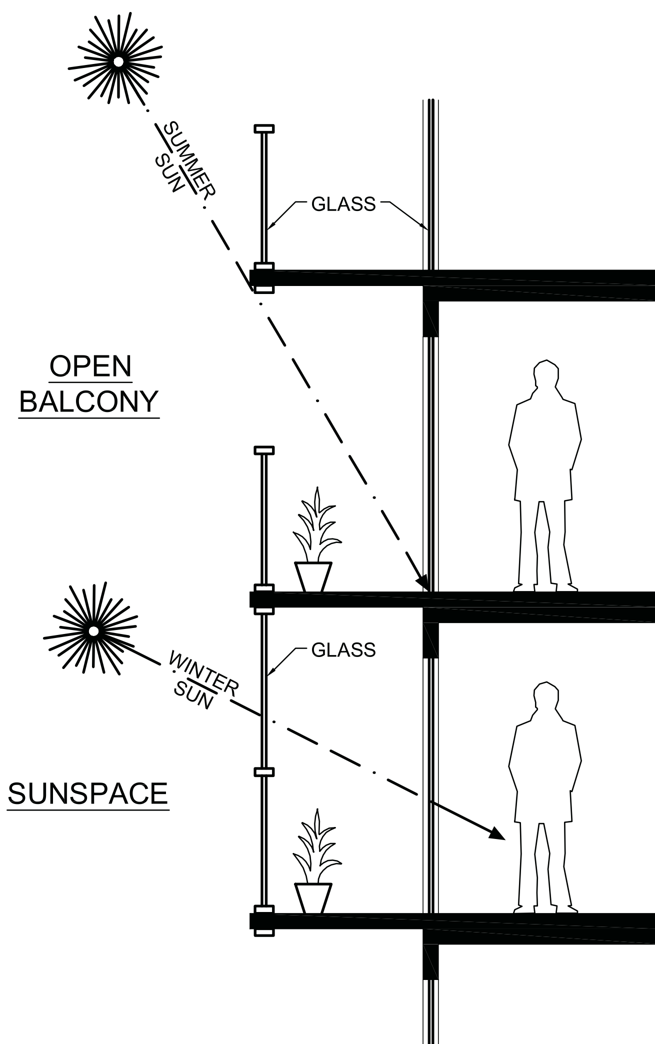


Figure 7.16f Balconies or covered porches that effectively shade windows or glass doors in the summer unfortunately also block much needed sun in the winter. By enclosing the balconies with glazing during the winter, valuable sunspaces can be created.

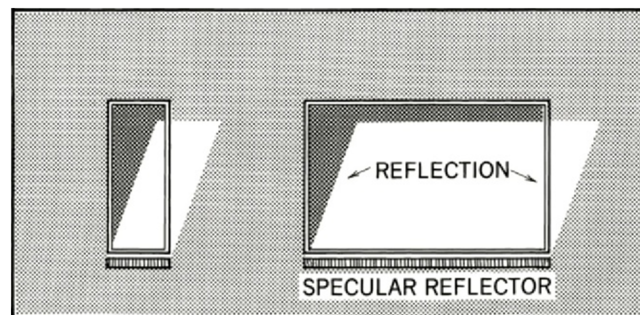


Figure 7.16g Specular reflectors are much less efficient on narrow than on wide windows. The diagram shows how on a south orientation the afternoon sun is reflected toward the east side of the window.

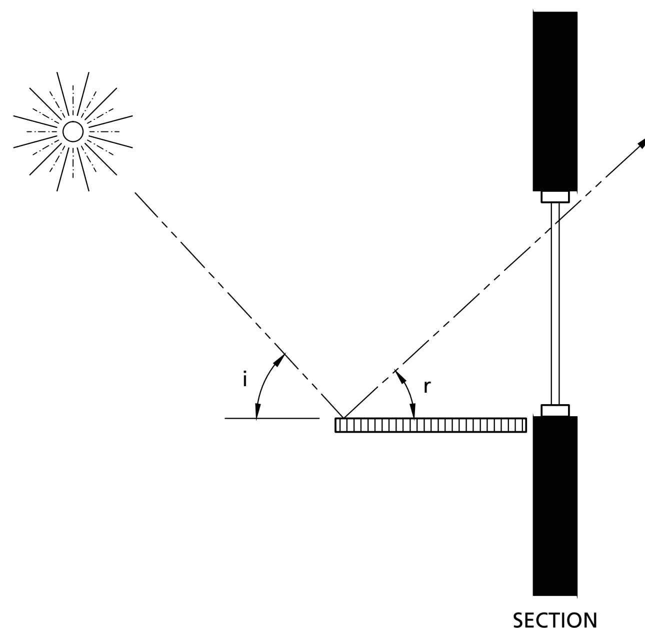


Figure 7.16h The length of a specular reflector is determined by the sunray that just clears the window head.

Effective night insulation can be achieved with thick or tight woven drapes or drapes with a thermal foam liner. Cellular shades are quite popular, and most effective is a roll-down quilt system.

Using high R-value windows on the south facade is not recommended because as the R-value goes up the solar heat gain goes down. Also, windows by themselves do not provide for privacy, summer shading, and the elimination of the "black hole" effect at night. Night insulation is discussed further in Section 15.10.

Fans

Heating a building only by passive means is not always the best policy, because fans can often make a passive system more effective. For example, in a direct-gain system, excessive heat can be moved to non-solar-heated spaces with a fan. If the backup mechanical system is an air system, then the air-handling unit can distribute the excessive heat, and if not, a small exhaust type fan in indoor partitions can be used. When a passive system is helped with a fan, it is sometimes called a hybrid system, but if the fan power is small, it can be called an enhanced passive system.

Auxiliary Heating

Almost every passive solar system needs an auxiliary heating system, especially for cold cloudy days. For those living in rural areas, a wood-burning stove may be appropriate, but for most buildings a backup conventional heating system should be provided.

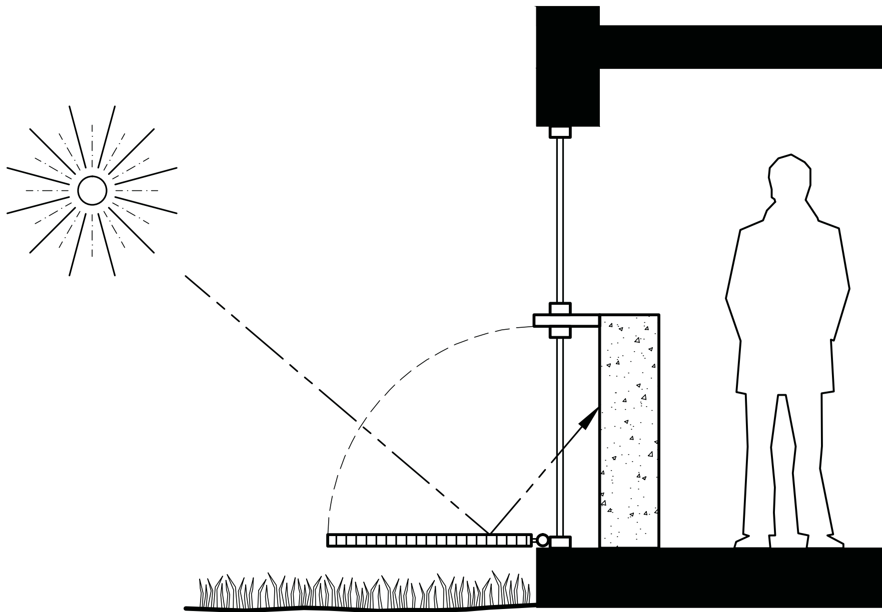


Figure 7.16i Specular (mirror-like) reflectors can improve the performance of passive solar systems. However, they must be removed to prevent summer overheating. In some cases, as in this figure, they can be used for shading in the summer.

7.17 HEAT-STORAGE MATERIALS

The success of passive solar heating and some passive cooling systems depends largely on the proper use of heat-storage materials. When comparing various materials for storing heat in buildings, the architectural designer is mainly interested in the heat capacity in terms of the energy per volume rather than weight. Figure 7.17a shows the large variation in volumetric heat capacity among materials.

Air, for example, is almost completely worthless as a heat-storage material because it has so little mass. Insulation, too, can store only insignificant amounts of heat because it consists mostly of air. Water, on the other hand, is one of the best heat-storage materials, and steel is almost as good. Except for wood, it seems that the heavy materials are good and the light materials are bad for storing heat. Although wood has a high heat capacity because of its water content, it is only slightly suitable for heat storage because it has a low conductance of heat, which prevents the center of a mass of wood from participating efficiently in the storage of heat. See Figure 7.17b for the conductivity of some ordinary materials. Thus, for a material to be a good heat-storage medium, it must have both a high heat capacity and high conductance (Fig. 7.17c). For this reason water, steel, brick, concrete, and stone are some of the best choices.

Water is an excellent heat-storage material not only because it has the highest heat capacity of any material but also because it has a very high heat-absorption rate. In water, natural convection currents as well as conduction help to move the heat to the whole mass (Fig. 7.17d). Because of the somewhat slow conductance of heat in concrete, brick, stone, etc., the thermally effective thickness of these solids is limited. Although concrete, stone, brick, and adobe are not as efficient as water when it comes to storing heat, they have a number of advantages. They don't leak or freeze, and they usually also serve as the structure. Tables 7.7b and 7.10, which are used to estimate the required thermal mass, give the optimum thickness of the mass. When more heat storage is required, the surface area and not the thickness should be increased.

There are even more efficient materials for storing heat. These are called phase-change materials (PCM). They store the energy in the form of latent heat, while the previously

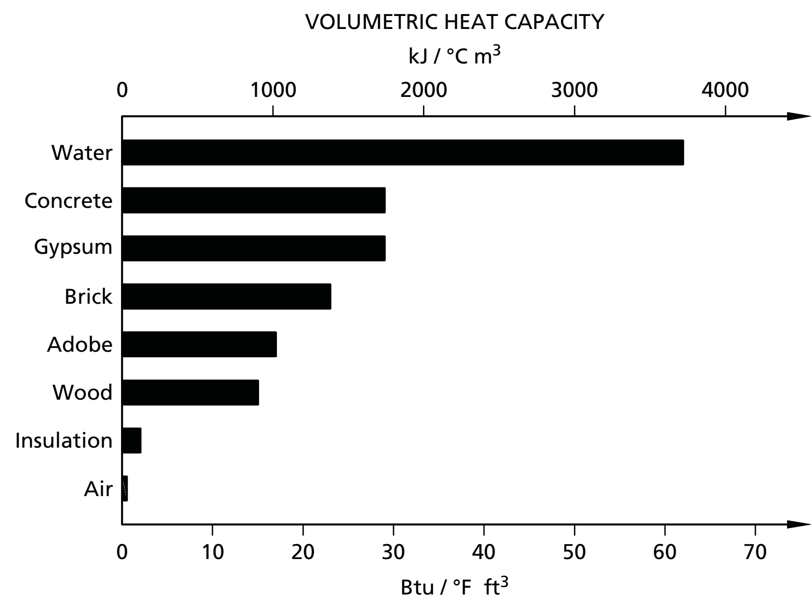


Figure 7.17a The volumetric heat capacity of common building materials is shown.

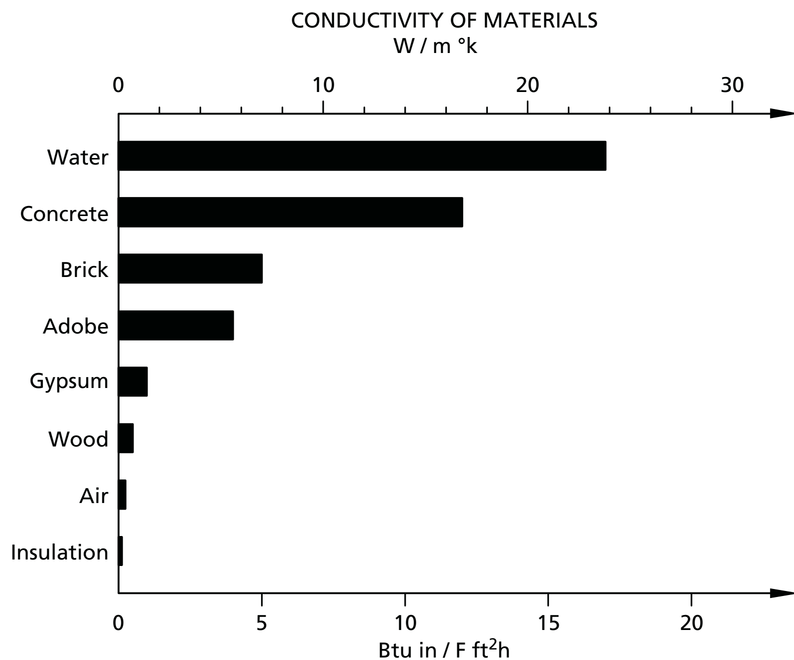


Figure 7.17b The thermal conductivity (reciprocal of resistance) of various building materials is shown.

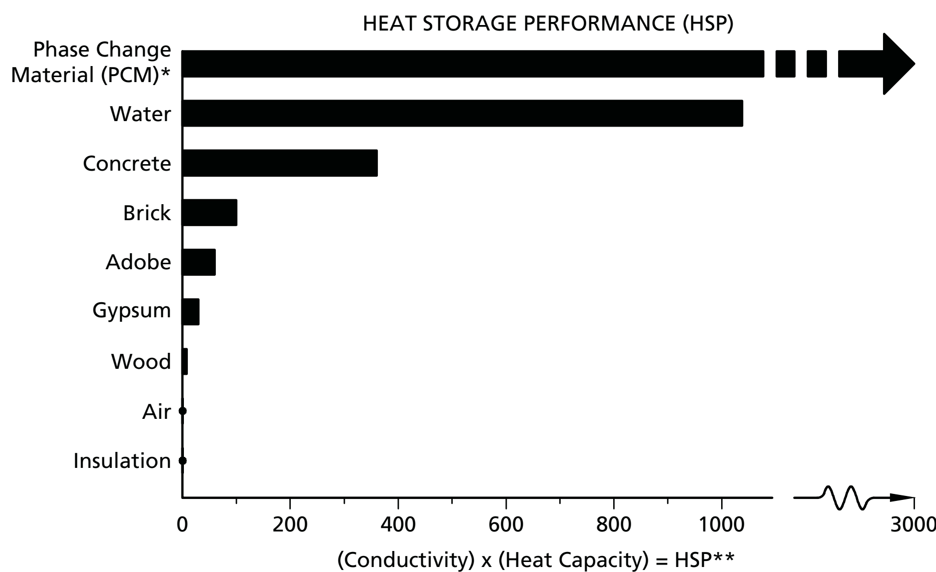


Figure 7.17c The ability of a material to store heat is a function of both heat capacity and conductivity. The combined effect is called heat-storage performance (HSP).

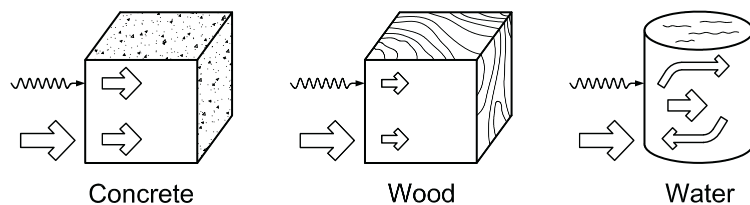


Figure 7.17d Because the conduction of heat into the interior of a material is critical for heat storage, wood is not good for storing heat, while water is excellent.



Figure 7.17e To maximize the exposure area, this PCM material comes ¾ in (2 cm) thick PCM capsules attached to it which will be in contact with the interior side of gypsum boards covering the ceiling and the walls. (Courtesy of Andrew Michler, PUSHpassive-Rocky Mountain Passive Homes)

Table 7.17 Comparison of Various Heat-Storage Materials

Material	Advantages	Disadvantages
Water	Quite compact Free	A storage container is required, which can be expensive Leakage is possible
Concrete, stone, or brick	Very stable Can also serve as wall, floor, etc.	Expensive to buy and install if only used to store heat
Phase-change material (PCM)	Most compact Can easily fit into ordinary frame construction	Most expensive

mentioned materials store the energy as sensible heat. In passive heating, the phase change must occur near the comfort zone (68°–78°F [20°–25°C]), paraffin and the salt hydrates (e.g., calcium chloride hexahydrate and Glauber's salt) are the most used phase-change materials.

Because PCM materials are a liquid part of the time, they need to be encased or encapsulated, The material is available in containers that fit between studs, embedded in gypsum boards, or in sheets that fit between studs and joists (Fig. 7.17e). From Figure 7.17c it can be seen that phase-change materials can store three times as much heat as water and nine times as much as concrete. See Table 7.17 for a comparison of various heat storage materials.

Where thermal mass is not present for other reasons, such as part of the structure, its use becomes an additional cost. For the many buildings that have slabs on grade or concrete floors, the mass is free and located in the ideal location, since the floor next to the south windows receives by far the most direct sun. However, the slabs may not be covered by an insulating material such as carpets. The least expensive solution is to leave the concrete exposed using either a colored admixture or an acid stain, which has become very popular (Colorplate 1). If a floor covering is used, it must be conductive like ceramic tile or stone.

Even when extra mass is added to a building, it is important to remember that thermal mass is useful for more than just saving energy year-round; if structural, it can also provide resilience especially from storms.

Thermal mass is useful for passive solar, passive cooling, and air-conditioning!

7.18 OTHER PASSIVE HEATING SYSTEMS

Convective-Loop System (Thermosiphon)

Figure 7.18a shows the basic elements of a convective-loop system. The solar collector generates a hot fluid (air or water) that rises to the storage area. Meanwhile, the cooler fluid sinks from storage and flows into the collector. This flow by natural convection is also called **thermosiphoning**. At night, the convection currents would reverse if the storage container were not located higher than the collector. The key to success in this system, therefore, is to place the thermal storage at a higher elevation than the collector. Unfortunately, this is usually difficult to do because of the weight of the water or rocks that are the typical storage mediums. Placing such as mass in an elevated position can be quite a problem unless you are lucky enough to have a building site that slopes down steeply to the south (Fig. 7.18b).

Roof Ponds

Roof ponds are similar to Trombe walls except that the thermal storage is on the roof. In this roof-pond system, water is stored in black plastic bags on a metal deck roof, and during a winter day the sun heats

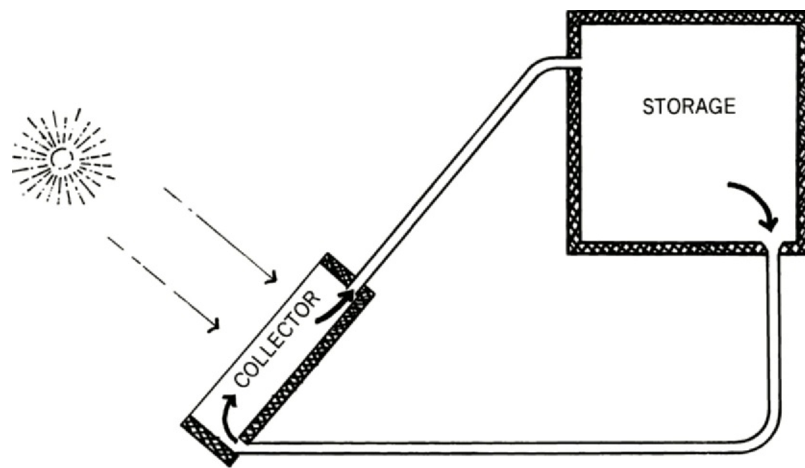


Figure 7.18a The passive convective loop (thermosiphon) system requires the storage to be above the collector.

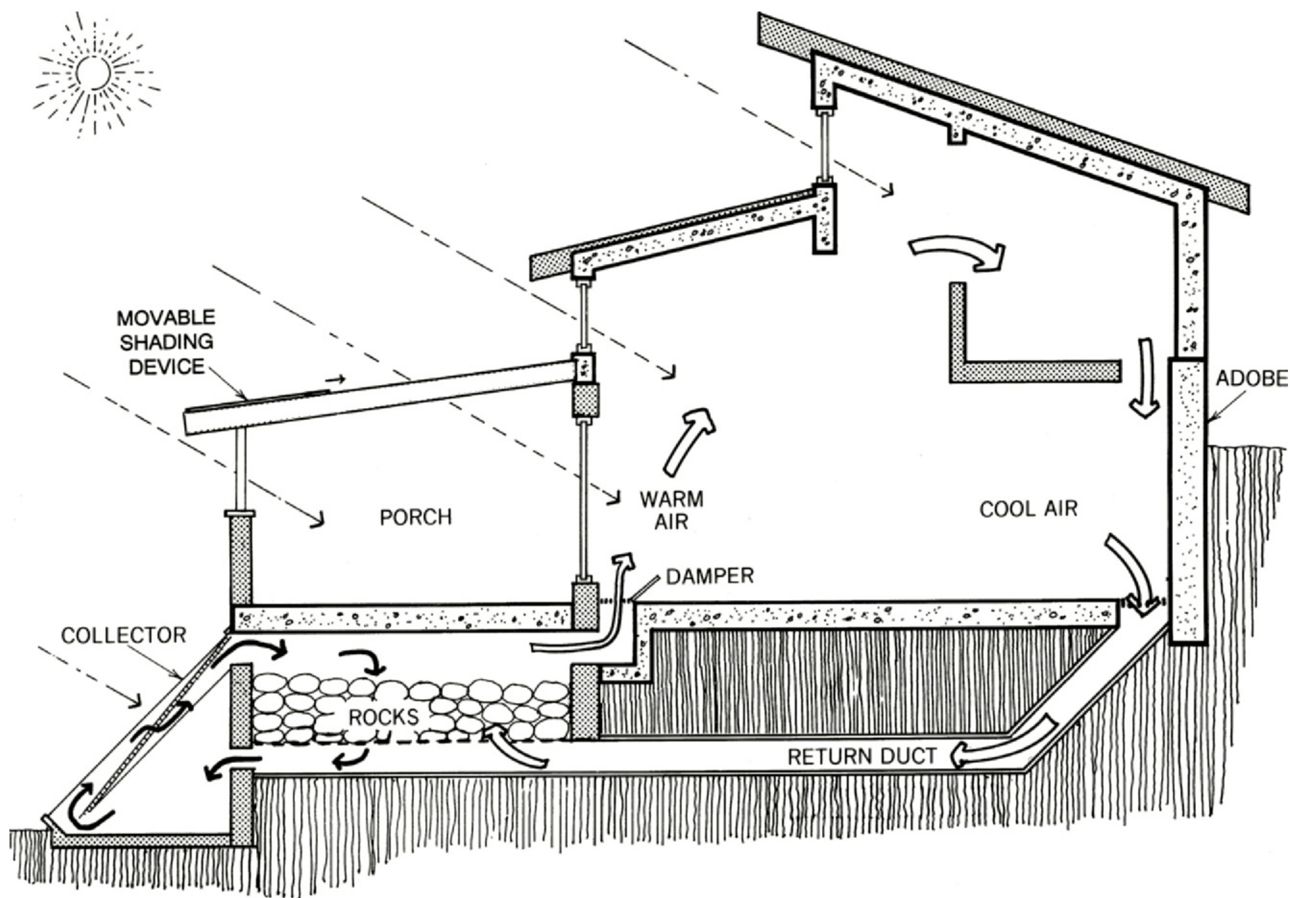


Figure 7.18b A convective loop heats the rock bed, and a second convective loop heats the building at night. Davis House, Corrales, New Mexico, designed by Steve Baer.

the water bags (Fig. 7.18c). The heat is conducted down in the water and radiated from the ceiling into the living space. At night, movable insulation covers the water to keep the heat from being lost to the night sky (Fig. 7.18d).

In theory, the roof pond is an attractive system because it not only heats passively in winter but can also give effective passive cooling in the summer. During the overheated part of the year, the insulation covers the house during the day and is removed at night. This passive

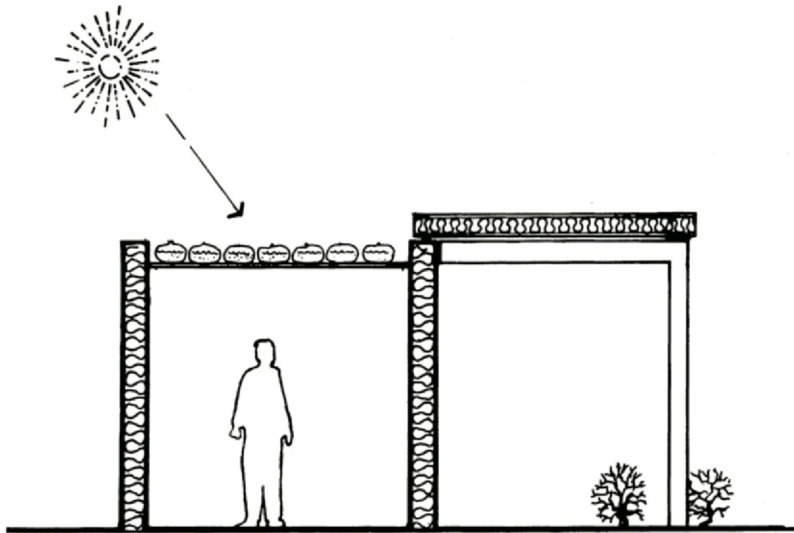


Figure 7.18c During a winter day, the black plastic bags of water are exposed to the sun in the roof-pond system.

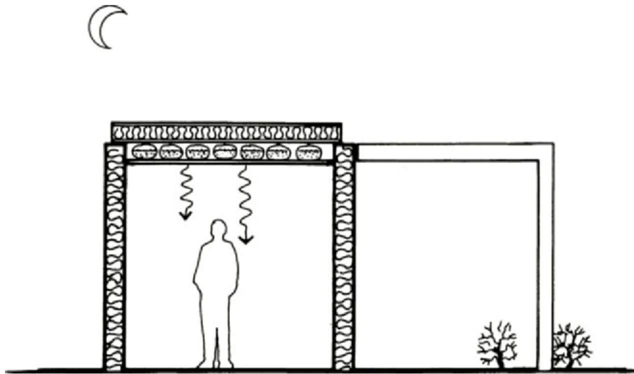


Figure 7.18d During a winter night, a rigid insulation panel is slid over the water.

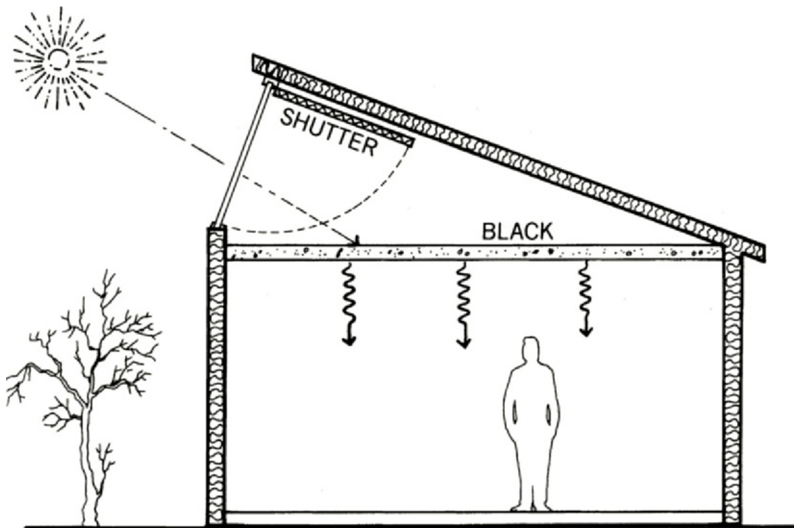


Figure 7.18e The roof radiation trap system developed by Givoni in Israel is shown.

cooling strategy is explained further in Section 10.11.

Unfortunately, this concept has some serious practical problems. One difficulty is that no one has been able to develop a workable, movable insulation system for the roof. Another problem is the weight of the water and potential water leakage. And most importantly, because of the cosine law, flat roofs receive less solar radiation than sloped or vertical surfaces in the winter. The higher the latitude, the worse this problem becomes. Therefore, roof ponds are best for latitudes below 30° that have cold winters, as can be found at high elevations.

Roof Radiation Trap

To overcome some of the serious difficulties with roof ponds, Baruch Givoni developed the roof radiation trap system. As shown in Figure 7.18e, the glazing on the roof is tilted to maximize winter collection at any latitude (tilt = latitude + 15°). After passing through the glazing, the solar radiation is absorbed by the black-painted concrete ceiling slab. The building is, thus, heated by radiation from the ceiling. The sloped roof is well insulated, and a movable shutter can reduce heat loss through the glass at night. This system can also be adapted for summer passive cooling by evaporation and is described further in Section 10.12.

Lightweight Collecting Walls

The lightweight collecting wall shown in Figure 7.18f is useful in very cold climates for those types of buildings in which extra heating is required during the day and little heat is required at night, which is typical of many schools, office buildings, and factories. Since there is no special storage mass in this system, all of the solar radiation falling on the collector is used to heat the interior air while the sun is shining.

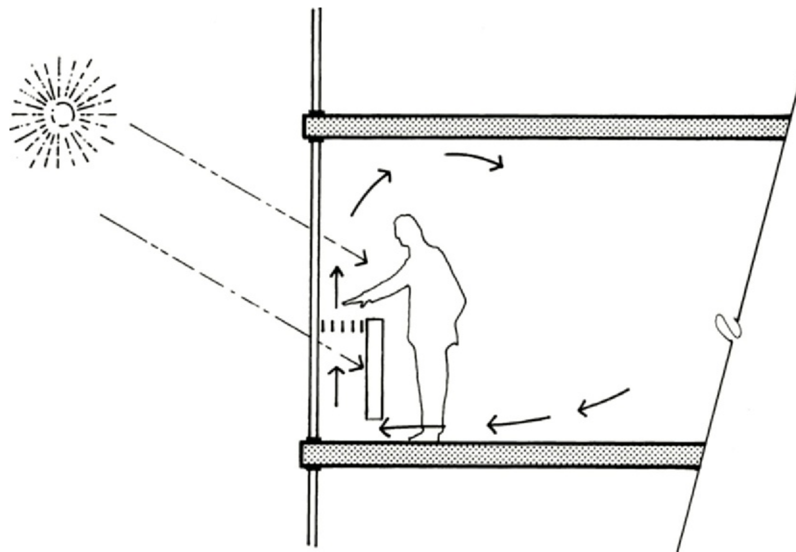


Figure 7.18f A lightweight collecting wall can supply additional daytime heating by natural convention and radiation without the introduction of excessive light.

7.19 MAXIMIZING PASSIVE SOLAR

Maximizing passive solar is one of the critical strategies for fighting global warming because it reduces the need for burning fossil energy. Use the following rules of thumb to maximize the performance of a passive solar design.

Rules of Thumb for Maximizing Passive Solar

1. Orientation, orientation, orientation—orient as much glazing as possible to the south or within 20° of south.
2. Use glazing on south windows with a high solar heat gain coefficient (SHGC) rather than a great R-value.
3. Use as much thermal mass as possible. A floor slab receiving direct solar radiation is best. Maximize the surface area of the mass rather than thickness.
4. Use water or PCM for the most compact heat storage.
5. Use indoor night insulation, especially on south windows, to reduce both winter nighttime heat loss and summer daytime heat gain whenever light and view are not needed (e.g., in homes during weekdays). East, west, and north windows can use high performance windows.
6. Glazing must be fully shaded in the summer. Use a movable shading device such as an awning on south windows to achieve 100 percent solar exposure in the winter and 100 percent shading in the summer.
7. Make full use of the south facade for collecting the winter sun by using a combination of direct gain and Trombe wall.
8. Trombe walls must be shaded (covered) in the summer to prevent unnecessary heat gain.
9. Use night insulation for Trombe walls.
10. The combination of effective summer shading and winter night insulation (used during the day in the summer) makes it unnecessary to limit the amount of south glazing. Excess heat in solar-heated spaces should be blown to non-solar-heated spaces.

7.20 CONCLUSION

It has often been said that there is no such thing as a free lunch. However, the benefits of using orientation correctly are a free lunch. As stated before, passive solar is 80 percent orientation. Thus, orienting windows to the south yields free energy. The chart in Figure 7.20 shows that only south windows have a net gain on a cold January day in Salt Lake City, Utah. Merely by moving the windows to the south wall, passive solar heating is achieved—a free lunch (Case 2 in Fig. 7.20). As will be seen in Chapter 9, another free lunch is available in the summer by using orientation correctly.

Not only are passive heating systems a vital strategy for sustainability, they also provide passive security (resilience) when the normal supply of energy is interrupted or becomes too expensive. Pipes and people will never freeze in a passive solar building. Even without backup heating, the temperature will not go below 55°F (13°C) in a cold and sunny climate or below 45°F (7°C) in a cold and cloudy climate.

In urban areas and far northern latitudes, solar access may not be available for passive systems but may still be available high on the roof. In such cases, solar heating can still be achieved by active solar systems described in the next chapter.

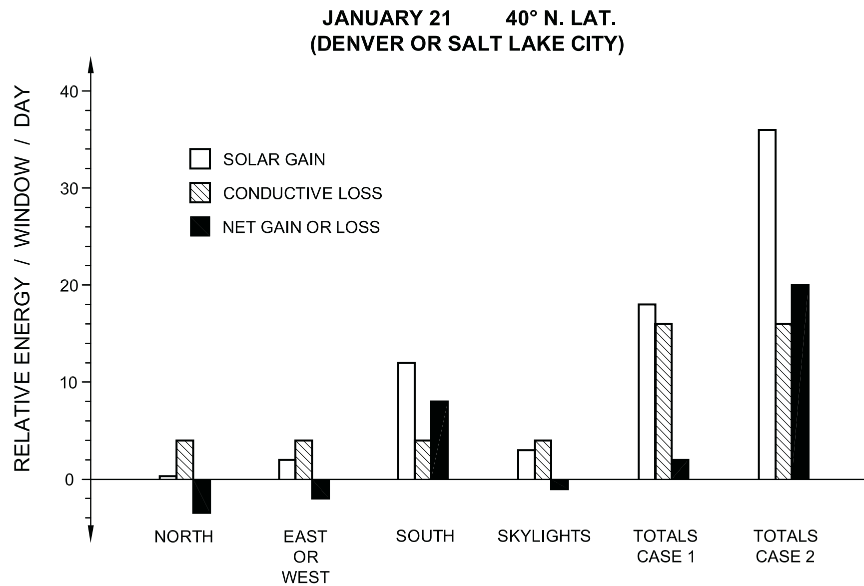


Figure 7.20 The benefits of orientation are made clear from this study of heat gain and heat loss for windows on various walls on a cold winter day. As can be seen, only south windows capture more heat from the sun than they lose in a twenty-four-hour period. Case 2 demonstrates the benefits of placing all the windows on the south wall. Remember, passive solar is 80 percent orientation.

KEY IDEAS OF CHAPTER 7

1. Maximize south-facing glazing because south windows
   a. Collect much more sun during the day than they lose at night
   b. Collect much more sun in the winter than in the summer
2. Passive solar heating consists essentially of south-facing glazing and thermal mass.
3. In a direct-gain system, the more mass receiving direct or reflected solar radiation, the better. The mass should have a large surface area rather than depth.
4. The three main passive solar systems are
   a. Direct gain
   b. Trombe wall
   c. Sunspace
5. Direct-gain systems are the simplest and most economical but result in high light levels.
6. Trombe walls supply heat without light.
7. Sunspaces are delightful living spaces as well as solar heaters.
8. To keep a sunspace from being an energy liability, one must design it to be a semitemperate living space (i.e., neither mechanically heated nor cooled).
9. Passive systems must be shaded in summer to prevent an asset from becoming a liability.
10. Passive solar is 80 percent orientation.
11. Passive solar provides security against power outages and high energy prices.
12. Some passive solar systems can be a "free lunch" because they can save money without the need to spend money.
13. Passive solar is a vital strategy for sustainability.

Resources

FURTHER READING

(See the Bibliography in the back of the book for full citations.)

Anderson, B. *Solar Energy: Fundamentals in Building Design*.

Anderson, B., and M. Wells. *Passive Solar Energy*.

ASHRAE. *Passive Solar Heating Analysis: A Design Manual*.

Bainbridge, D, and K. Haggard. *Passive Solar Architecture*.

Balcomb, J. D. *Passive Solar Buildings*.

Boonstra, C., ed. *Solar Energy in Building Renovation*.

Brown, G. Z., and M. DeKay. *Sun, Wind, and Light: Architectural Design Strategies*, 2nd ed.

Buckley, S. *Sun Up to Sun Down*.

Clegg, P., and D. Watkins. *Sunspaces: New Vistas for Living and Growing*.

Cook, J. *Award Winning Passive Solar House Designs*.

Daniels, K. *The Technology of Ecological Building: Basic Principles and Measures, Examples and Ideas*.

Givoni, B. *Climate Considerations in Building and Urban Design*.

Heinz, T. A. "Frank Lloyd Wright's Jacobs II House."

Hestnes, A. G., R. Hastings, and B. Saxhof, eds. *Solar Energy Houses: Strategies, Technologies, Examples*.

Jones, R. W., and R. D. McFarland. *The Sunspace Primer: A Guide to Passive Solar Heating*.

Kachadorian, J. *The Passive Solar House: Using Solar Design to Heat and Cool Your Home*.

Kohlmaier, G., and B. von Sartory. *Das Glashaus: Ein Bautypus des 19. Jahrhunderts*.

Kwok, A., and W. Grondzik. *The Green Studio Handbook: Environmental Strategies for Schematic Design*.

Los Alamos National Lab. *Passive Solar Heating Analysis: A Design Manual*.

Mazria, E. *The Passive Solar Energy Book*.

Miller, B. *Buildings for a Sustainable America: Case Studies*.

Panchyk, K. *Solar Interior: Energy Efficient Spaces Designed for Comfort*.

Potts, M. *The New Independent Home: People and Houses That Harvest the Sun*.

Singh, M. *The Timeless Energy of the Sun for Life and Peace with Nature*.

Stein, B., J. Reynolds, W. T. Grondzik, and A. G. Kwok. *Mechanical and Electrical Equipment for Buildings*, 10th ed.

Steven Winter Associates. *The Passive Solar Design and Construction Handbook*.

Watson, D. *Designing and Building a Solar House: Your Place in the Sun*.

PERIODICALS

Solar Today

ORGANIZATIONS

(See Appendix K for full citations.)

American Solar Energy Society www.ases.org

Florida Solar Energy Center (FSEC) www.fsec.org

National Renewable Energy Laboratory (NREL) www.nrel.gov

Sustainable Buildings Industry Council (SBIC) www.sbic.org

CHAPTER 8

PHOTOVOLTAICS AND ACTIVE SOLAR

In real estate the mantra is:

location
location
location

In solar design the mantra is:

orientation
orientation
orientation

How can it be that the people of Turkey, Israel, and China can afford solar hot-water heaters while Americans can't?
Anonymous

8.1 INTRODUCTION

Although, from a distance, photovoltaic (PV) and active solar collectors appear quite similar, they produce distinctly different forms of energy. **PV panels** produce the very high-grade energy of electricity, while **active solar panels** produce the low-grade thermal energy of low-temperature heat. Electricity is called a **high-grade energy source** because it can be used to do all kinds of work (generate light, move elevators, etc.), while low-temperature heat can do little more than heat water or a building.

These two systems are discussed in the same chapter because they are often mounted side by side on a building, they look similar, and their needs for orientation and tilt are similar. The term "solar panel" should not be used since it can apply equally well to either active solar or PV panels. PV panels are discussed first.

8.2 THE ALMOST IDEAL ENERGY SOURCE

As was mentioned in Chapter 2, the conventional energy sources all have serious drawbacks. What, then, would be the almost ideal energy source? What are the characteristics of the ideal energy source?

Characteristics of the Ideal Energy Source

1. Sustainable (renewable)
2. Nonpolluting
3. Not dangerous to people or the planet
4. High-grade energy useful for any purpose
5. Silent
6. Supplies power where it is needed (no need to transport energy)
7. Most available at peak demand time, which is frequently a hot, sunny summer day
8. Has the additional benefit of creating the building envelope (i.e., displaces conventional building materials)
9. High reliability
10. No moving parts
11. No maintenance required
12. Modular (can come in any size required)
13. Low operating cost
14. Low initial cost
15. Supplies energy all the time

PV is the only energy source that comes close to having these characteristics. PV meets or exceeds all except the last two characteristics: "low initial costs" and "supplies energy all the time." The fact that PV doesn't generate electricity at night is not as big a problem as it seems because when they are hooked up to the grid, they supply the grid during the day (especially during peak demand times), and they draw on the grid at night when the grid has extra capacity. In places where the grid is not available, batteries can store the electricity for times when the sun is not shining. The smart grid will be able to make efficient use of the mix of conventional power, wind power, solar power, and other renewable power sources.

Clouds reduce but do not eliminate electric generation, as the following rules of thumb indicate.

Cloudiness and PV-Output Rules of Thumb[1]

1. About 80 percent output on partly cloudy days
2. About 50 percent output on hazy/humid days
3. About 30 percent output on extremely overcast days

The cost of PV-generated electricity has dropped so much that its price is competitive with fossil and nuclear power in some parts of the United States, and as the graph in Figure 8.2a indicates, it is realistic to believe that the price will drop further.

As more PV is used, its cost will continue to decline through rapid technological improvements and the economics of scale (see Fig. 2.18b). PV has the potential to become very inexpensive because of its inherent simplicity and the very small amount of material that it requires. At the same time that PV becomes less expensive, it will become more attractive as more people recognize the need for a sustainable, clean energy source that does not produce any greenhouse gases.

Several countries have decided that PV needs to be implemented now. Even though Germany, Switzerland, and Japan all have relatively low exposure to solar irradiation, they are using PV widely. Germany reached an important milestone on one day in 2012 when half of its electricity was produced by renewable sources. It would be easier for the United States and much of the world to reach that level, because most of the world receives much more solar radiation than does Germany.

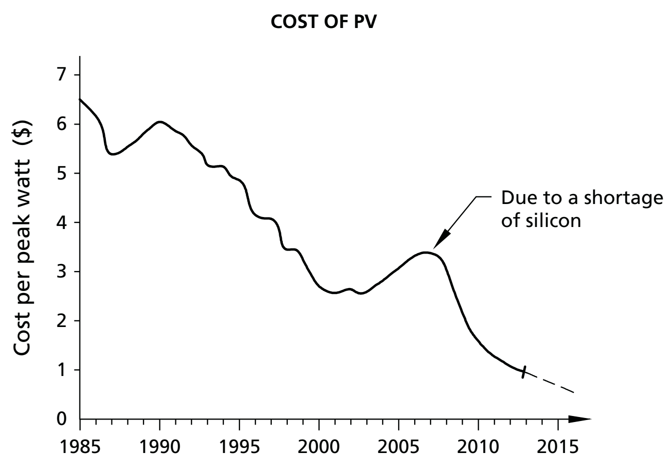


Figure 8.2a PV systems have experienced a dramatic decline in cost, and they are now competitive with fossil and nuclear power in some parts of the United States.

[1] From *Tapping into the Sun*.

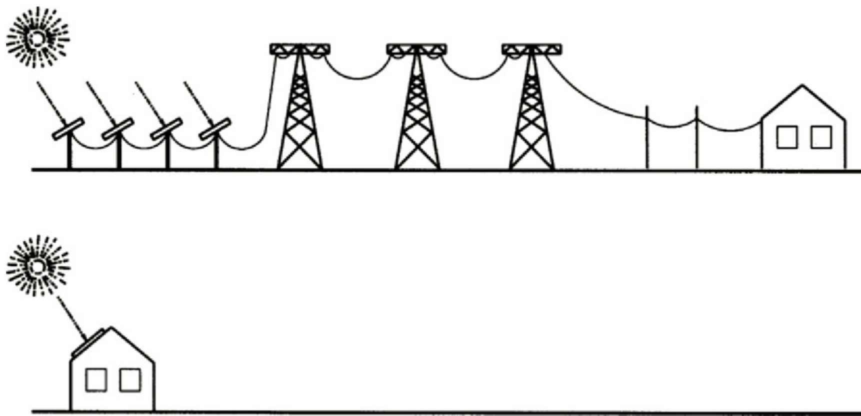


Figure 8.2b On-site PV eliminates electrical-transmission losses, which can be as high as 25 percent with the existing power grid.

One of the reasons for these countries to promote PV is climate change. Not only does PV electricity displace the fossil fuel needed to supply the electricity, it supplies electricity much more efficiently. Only about 30 percent of the source fossil fuel ends up as electricity in the building. Besides the many losses in generating electricity at the power plant (see again Figure 3.20), about 25 percent is lost in transmission, which is not the case with on-site generators (Fig. 8.2b).

8.3 HISTORY OF PV

Becquerel discovered the photoelectric effect in 1839, and Bell Laboratories developed the first crystalline silicon cell in 1954. Little practical progress was made until 1958, when the space program needed an extremely light and reliable source of electricity for its satellites. Although PV proved very reliable, the cost was initially too high for earthbound applications. However, continuing research, development, and mass production have reduced the cost of PV to make it practical almost everywhere. PV is especially useful in developing countries where villages are often far from the power grid, while in developed countries it supplies power to many buildings connected to the grid. In the developed world, many individuals, communities, and countries are motivated to use PV to address the issues of global warming, sustainability, and energy security (Figs. 8.3a–8.3c).



Figure 8.3a The Lord House in Maine is a grid-connected building with half of the roof generating electricity and the other half, hot water. During the day, electricity is sold to the power company, and at night it is bought back. The house is also passively heated and superinsulated. (Courtesy of Solar Design Associates, Inc.)



Figure 8.3b The Intercultural Center at Georgetown University is a fine example of building-integrated photovoltaics (BIPV). The south-facing roof is covered with a 300-kilowatt PV array that provides about 50 percent of the building's electrical needs. (Courtesy of and © BP Solarex.)



Figure 8.3c Several power companies have set up PV farms to harvest the sun. This energy is most available on hot, sunny summer days, precisely when it is needed to supply electricity for air-conditioning. Shown is the 2-megawatt, single-axis-tracking system of the Sacramento Municipal Utility District at Rancho Seco, California. The nuclear power plant, seen in the background, has been shut down. (Courtesy of the Sacramento Municipal Utility District.)

8.4 THE PV CELL

Photovoltaic (PV) cells, sometimes known as **solar cells**, are made from materials that convert light directly into electricity. Most use silicon with small amounts of certain impurities added to create an excess of electrons in one layer and a lack of electrons in another layer. Photons of light create free electrons in one layer, and a conducting strip enables the electrons to flow through an external circuit to reach the layer that lacks electrons (Fig. 8.4a).

Single-crystal silicon cells are the most efficient but also the most expensive. To reduce the cost, polycrystalline and thin-film PV cells have been developed. Thin-film PV is made of amorphous silicon, copper indium diselenide, or cadmium telluride. Although these cells convert sunlight into electricity at half the efficiency of the single-crystal silicon cells, their lower cost more than compensates whenever collector area is not limited (see Table 8.4). Continuing research is raising the efficiency of all cells, with 41 percent the highest reached in a laboratory so far.

Because most PV cells are small and fragile and produce only a small amount of power, a collection of cells is encased to form modules. Modules come in many sizes, but to make handling easy, they are rarely over 3 ft (1 m) wide and 5 ft (1.5 m) long. Some modules are combined to form panels, which are further combined to form an array (Fig. 8.4b).

Like batteries, when two cells or modules are connected in series, the voltage doubles; when they are connected in parallel, their current doubles. Thus, a sufficient number of cells in the right combination can produce any combination of voltage and current. Since electrical power is the product of voltage and current, any amount of power can be produced with enough cells (see Sidebox 8.4).

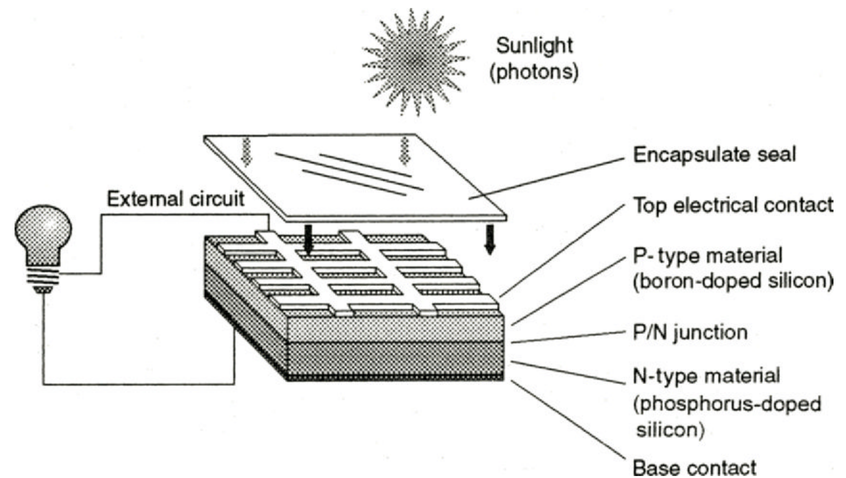


Figure 8.4a A section through a typical PV cell. Photons of light generate free electrons. The metal grid on the top and the metal plate on the bottom allow for the collection and return of the free electrons through an external electric circuit. (Drawing from Fact Sheet No. 11 from State Energy Conservation Office of Texas.)

Table 8.4 The Efficiency of PV Cells

Type of PV Cell	Efficiency Range (%)
Single-crystal silicon	16–22
Multicrystal silicon	14–17
Thin film	7–12

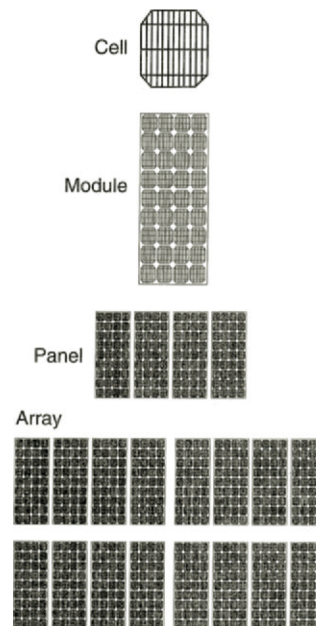


Figure 8.4b Cells combine to form modules, modules form panels, and panels combine to form an array. (From *Federal Technology Alert: Photovoltaics*.)

SIDEBOX 8.4

The electrical power produced is equal to the product of the current and voltage.

$$W = I \times V$$

where
W = power in watts
I = current in amperes
V = voltage in volts

The electrical energy produced is equal to the power times the amount of time that the power is produced.

$$E = W \times h$$

where
E = electrical energy in watt-hours
h = time in hours

Since the number of watt-hours is usually very large, electrical energy is usually measured in kilowatt-hours.

$$E = k \times W \times H$$

where
1 kW = 1000 W

8.5 TYPES OF PV SYSTEMS

Two basic types of PV systems exist for buildings: stand-alone and grid-connected. When connection to a power grid is not possible or not wanted, a stand-alone system is required. In such cases, batteries are needed to supply power at night on overcast days, and when peak power is required. The PV arrays are sized to handle both normal daytime loads and battery charging. The batteries add significantly to the cost and maintenance of the systems.

When PV is used where the power grid exists, batteries are not needed. During a sunny day, excess PV power is sold to the utility, and at night, power is drawn from the grid. In effect, the grid acts as a giant storage battery. This can be an advantage to both the PV owners and power companies, because the greatest demand on their grid is usually on hot, sunny summer days, while at night the power companies have excess capacity that they are eager to sell.

Right now, most people pay the average cost over a day and year for electricity, but with the deregulation of the power industry and with the smart grid, time-of-day pricing will become common. The price at peak hours is often so high that PV can already compete. **Net-metering laws** in many states require the power companies to buy PV power from individuals.

In a grid-connected system, an inverter is required to change the direct current from the PV array to alternating current (AC) at the correct voltage of the grid (Fig. 8.5a). All appliances in the building are then ordinary AC, 120v (or whatever the baseline voltage is). Note again that batteries are not needed, which is a significant saving of both money and maintenance.

In stand-alone systems, the excess electricity produced during the day is stored in batteries for nighttime and dark, cloudy days (Fig. 8.5b). Since inverters are expensive and can consume as much as 20 percent of the power the PV produces, buildings must use as many low-voltage direct-current (DC) appliances in place of standard AC appliances as possible. A small, less expensive inverter can then supply the AC appliances. Also, since PV cells and batteries are expensive, backup power is preferable over an extra-large PV system for lengthy overcast periods or storms. A hybrid system using wind power is often the ideal complement to PV because not only can the wind blow at night but it is usually extra windy during bad weather. Furthermore, in the winter, when there is less solar energy to harvest, it is usually windier than it is in the summer (Fig. 8.5c). Not all regions, however, are suitable for wind power. See the discussion of wind power in Chapter 2.

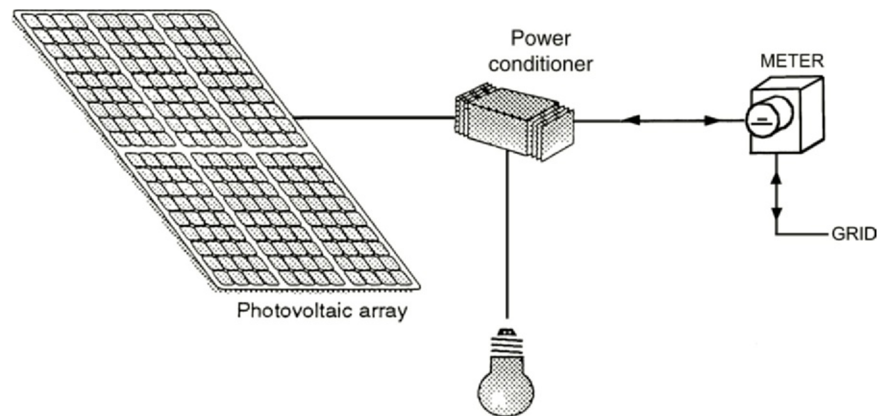


Figure 8.5a A typical grid-connected PV system. On a sunny day, the excess power will flow into the grid and the meter will run backward. The power conditioner contains an inverter to change DC into AC.

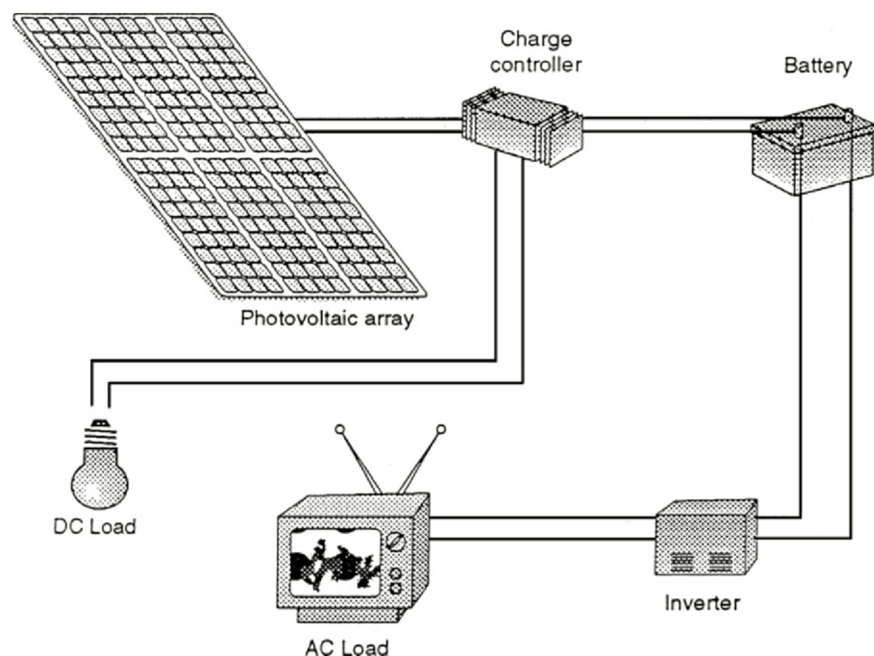


Figure 8.5b A stand-alone system needs batteries to store the electricity for nighttime use and an inverter to change DC to AC current.

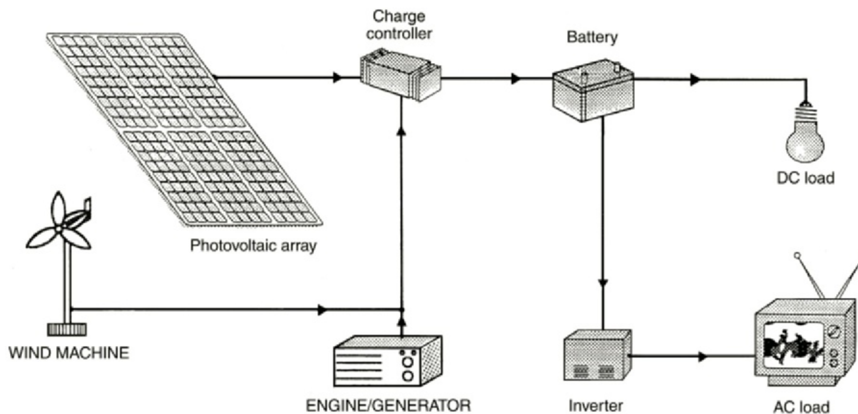


Figure 8.5c Hybrid systems give the most reliable power at the least cost for stand-alone installations.

When a reliable wind source is not available, an engine generator unit should be used to back up the PV system. It is reasonable to ask: why bother with the PV system at all? Why not just use the engine generator? Many remote installations that previously used only an engine generator are switching to the PV hybrid system because it is more reliable, requires much less maintenance, makes no noise, and needs little fuel, which is always a burden to bring to a remote site. In a well-designed hybrid system, the engine generator will operate only a few times a year, during unusually long cloudy periods.

8.6 BALANCE OF SYSTEM EQUIPMENT

A PV installation consists of the PV array and the **balance of system (BOS) equipment**. Typically, the BOS equipment comprises a charge controller, an inverter (for AC), switches, fuses, wires, etc. For stand-alone systems, the BOS equipment also includes the batteries. A small wall panel is usually sufficient for most of the BOS equipment except for the batteries.

In stand-alone systems, the excess electricity produced when the sun is shining is stored in batteries. For safety and long life, batteries should be stored in well-ventilated, cool, dry chambers. Batteries need to be vented outdoors because of the hydrogen that is produced during charging. Consequently, they should be stored either indoors next to an outdoor wall or in an insulated shed against the outside wall.

In the near future, an alternative to batteries might be the use of nonpolluting **fuel cells**. During the day, the sun will provide energy for the production of hydrogen via the electrolysis of water. At night, the fuel cell will generate electricity, and with hydrogen as the fuel, the only by-product will be water. Commercial fuel cells are now on the market.

8.7 BUILDING-INTEGRATED PHOTOVOLTAICS

PV systems can power buildings in a variety of ways, ranging from large-scale remote PV power plants to part of the building fabric. Some utilities are augmenting their electrical capacity through large, centralized PV farms (see Fig. 8.3c), while other power companies are setting up smaller PV fields closer to the electrical users. PV arrays can also be set up on the land adjacent to the building (Fig. 8.7a), placed on the roof (see again Fig. 8.3b), or integrated into the building envelope (Fig. 8.7b), in which case the phrase **building-integrated photovoltaics (BIPV)** is used. BIPV systems can replace the roofing, siding, curtain wall, glazing, or special elements such as overhangs and canopies.

There are a number of important benefits to using BIPV:

1. The avoidance of using valuable open space to mount the PV array
2. The avoidance of part of the cost of the building envelope by using PV modules instead
3. The avoidance of a support structure since the building structure exists anyway
4. The aesthetic potential of using a new type of cladding material
5. The benefit of generating all or at least a significant portion of the required electricity in an environmentally friendly way

Although at this time PV modules are still expensive, they are no more expensive than some premium architectural cladding. PV is not more expensive, for example, than granite or marble facing. Thus, one can save either all or part of the cost of the PV array by eliminating the cost of the building element being replaced.

PV modules come in many sizes, finishes, and colors. Most silicon cells are a beautiful blue color, with the crystalline structure forming an attractive pattern (Fig. 8.7c). Many thin-film PV modules are dark brown, and some are flexible so that they can be used on curved surfaces (Fig. 8.7d). Cells are now being developed that are gold, violet, or green in color. A variety of semitransparent PV modules can be used as glazing. Cells can be round, semicircular, octagonal, square, or rectangular, and custom modules and panels can be produced for large projects.

There are four major parts of the building envelope into which PV can be integrated: walls, roofs, glazing, and ancillary structures such as overhangs, entrance canopies, and shading structures for parking areas. Each of these building parts will be discussed in some detail after a



Figure 8.7a An onsite but not on building PV array requires a support structure and some open land for solar access. A sun-tracking system is shown. (Courtesy of the Ecological Design Institute.)



Figure 8.7b The building-integrated PV (BIPV) standing-seam roofing on this Maryland townhouse (at the center) is almost indistinguishable from conventional, standard-seam roofing on the other buildings. (Courtesy of United Solar Systems Corp., UNI-solar Photovoltaic Roofing.)

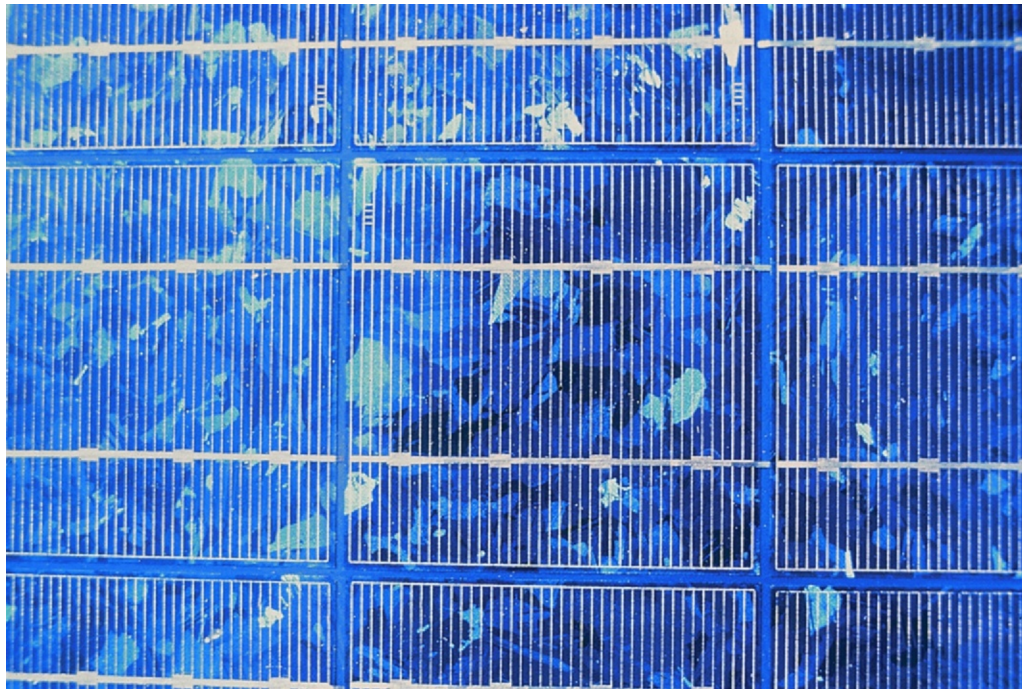


Figure 8.7c PV modules can be very attractive, as shown in this blue pattern of polycrystalline silicon cells.



Figure 8.7d Because thin-film modules are flexible, they are easily integrated into curved architecture.

short discussion of the PV characteristics that are important in building integration.

Since the PV modules are fairly dark in color and *must not* be shaded, much heat is produced, which not only degrades the performance of the PV cells but also may heat the building. Thus, cooling the cells is an important concern and will be discussed later. Also important are the orientation and tilt of the PV array, which will be discussed next.

8.8 ORIENTATION AND TILT

The maximum collection of solar radiation occurs when the collector is perpendicular to the direct beam radiation. Since the sun moves both daily and annually, only a two-axis tracking collector can maximize the collection over a year. Tracking collectors excel in sunny, dry climates, which have mostly direct beam radiation. In most sunny and humid climates, only about one-half of the solar radiation is direct, while in cloudy climates 80 percent or more of the radiation

is diffuse. When PV cells were very expensive, it made good sense to invest in a tracking device in most climates (see Fig. 8.7a). Now tracking collectors should be considered mostly for very sunny climates, and even there, the advantages of fixed PV may be greater than the benefits of tracking.

Even with fixed PV, orientation and tilt should still be considered. The best tilt for a PV array is primarily a function of the time of year that maximum power is required. Hot climates need the most electricity in the summer for air-conditioning, while cold climates need maximum electricity in the winter for lighting and for heating-system pumps and blowers. Use the design guidelines in Section 8.16 for choosing the optimum tilt for the PV.

Usually, the optimal orientation is due south, but there is little loss up to 20° east or 20° west of south. The daily-load profile, however, can influence the orientation. For example, elementary schools that start early in the morning and end in the middle of the afternoon should have the array facing about 30° east of south; in a climate with a morning fog, a southwest orientation would be appropriate. Since peak electrical demand usually occurs on hot, sunny summer afternoons, the PV module could also be facing west.

As PV modules get less expensive, the optimal orientation and tilt will become less important. Already, it makes sense to cover the roof and sometimes the south facade, which can generate about 70 percent as much as the roof. East and west facades are not far behind because they can produce up to 60 percent of the optimal south output. Eventually, all orientations except north could be clad with PV.

8.9 ROOFS CLAD WITH PV

Ideally, the roof should have the slope (tilt) described in Figure 8.16, with the PV replacing the roofing or on the roof. On flat roofs, a support structure can offer the ideal tilt, but, of course, the benefits of building integration are lost (Fig. 8.9a). A sawtooth clerestory is superior to a flat roof because the north-facing slope can be glazed for daylighting, while the south slope supports the PV (Fig. 8.9b). The south-facing PV can also be of the transparent kind, so that the clerestories can face south to both collect daylight and generate electricity. Also, sloped roofs are easier to waterproof. A flat slope is usually not desirable for the PV because it is too far from the ideal tilt (except near the equator) and because of dirt and snow accumulation. In northern latitudes, a vertical orientation may be best in order to avoid snow

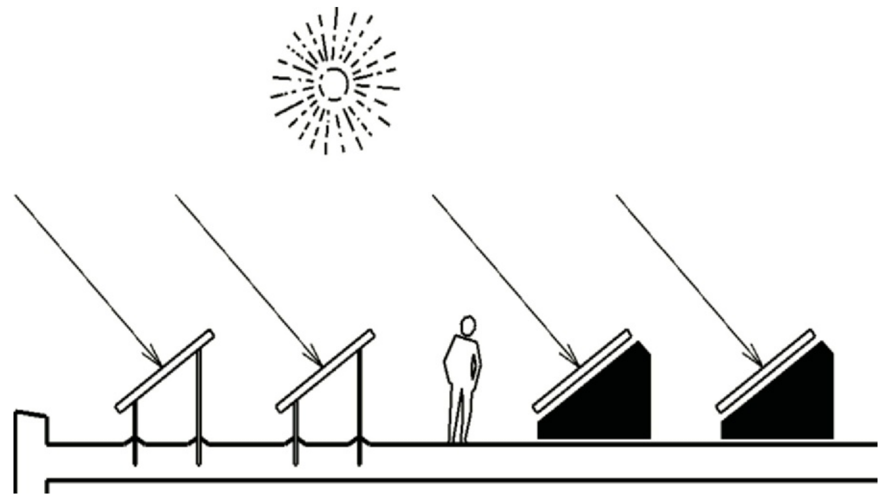


Figure 8.9a Support structures can provide the appropriate tilt for the PV on flat roofs, but they do not provide the benefits of being building integrated. The use of heavy concrete or gravel-filled support structures makes it unnecessary to penetrate the roof membrane.

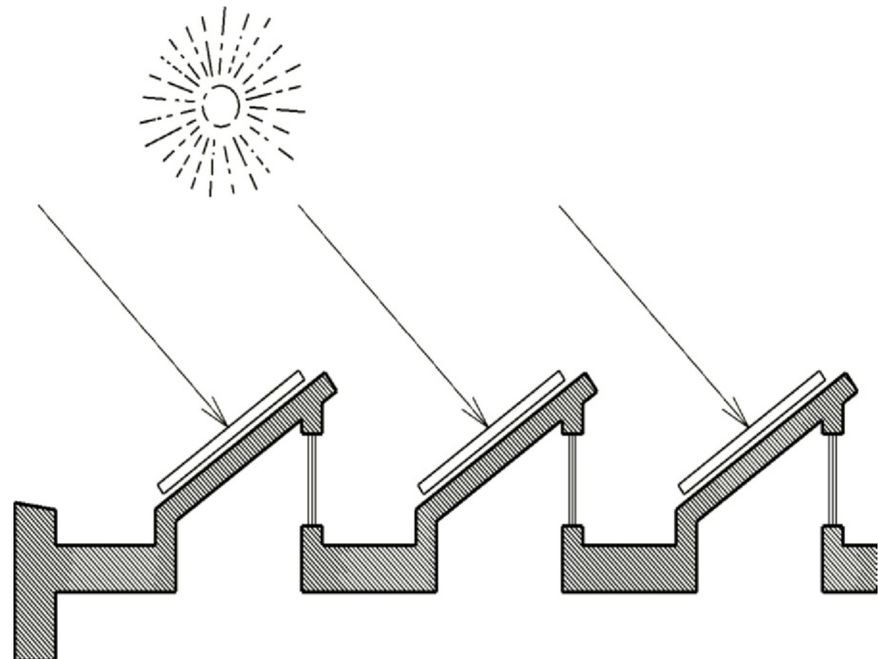


Figure 8.9b Sawtooth clerestories can provide both daylighting and the proper tilt for BIPV.

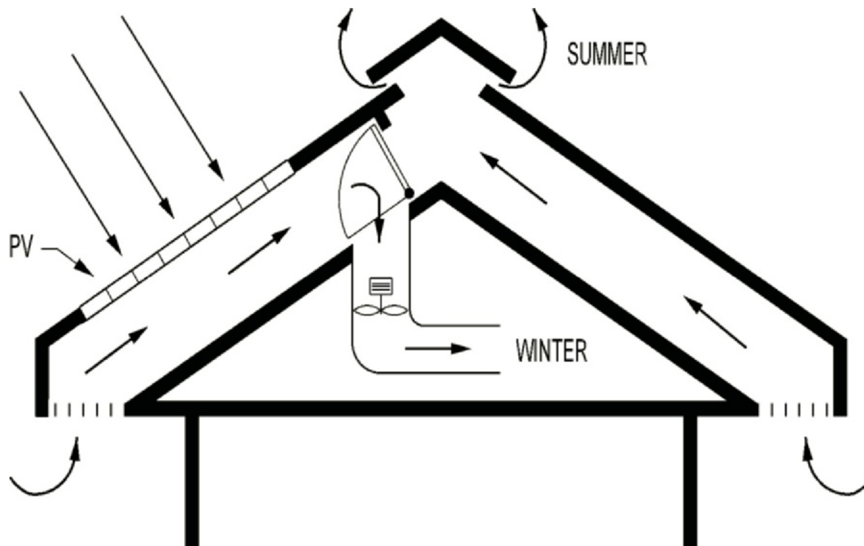


Figure 8.9c Ventilate the underside of the PV in summer to keep the cells from overheating. In winter, this warm air can be used to heat the building.



Figure 8.9d PV shingles are designed to blend in with standard shingles. (Courtesy of United States Solar Systems Corp., manufacturing solar roofing under the brand name UNI-solar.)

accumulations while benefiting from the snow's solar reflection.

If the PV is integrated into the roof, the underside needs to be ventilated to cool it. In winter, this waste heat can be collected to heat the building (Fig. 8.9c). For more traditional roofs, PV shingles, slates, and tiles are available. They are used in the conventional manner except that an electrical connection must be made with every unit (Fig. 8.9d).

8.10 FACADES CLAD WITH PV

Not only south but also east and west facades can be clad with PV and still generate a significant amount of electricity. If mullions are used on the exterior, they should be as shallow as possible to prevent shading of the PV (Fig. 8.10a). If the lower facade is shaded, as is common in dense urban areas or on sites with many trees, then use PV only on the upper part of the facade (Fig. 8.10b). As with the roof, it is best to leave an airspace behind the PV to cool the panels, and in winter this warm air can be collected to heat the building (Fig. 8.10c).



Figure 8.10a The APS Building in Fairfield, California, uses thin-film PV integrated into the curtain wall, skylight, and awning. (Courtesy of Kiss & Cathcart, architects. © Richard Barnes, photographer.)



Figure 8.10b The New York City skyscraper at 4 Times Square uses BIPV spandrel panels only on floors 35 to 48, because the lower floors are shaded too much. (Courtesy of Kiss & Cathcart, architects.)

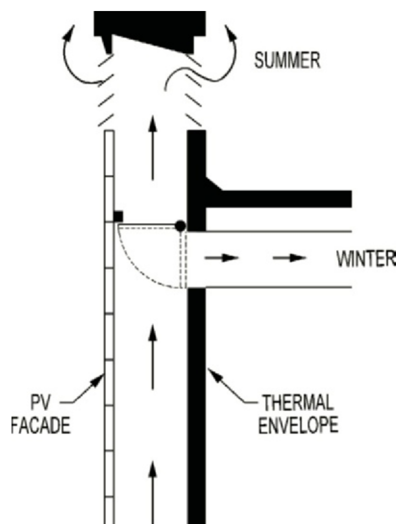


Figure 8.10c This double-wall design enables the air behind the PV to be vented in the summer to cool both the PV and the building. In winter, the hot air can be used to heat the north side of the building.

8.11 GLAZING AND PV

PV can be integrated into the building glazing in several different ways. The PV glazing can be transparent, translucent, louvered, or partially opaque. Because PV uses only part of the solar spectrum, the rest of the light can be allowed to pass through, and the view is maintained (Fig. 8.11a). The louvered PV type of glazing has narrow louvers covered with PV sandwiched between two layers of glass. Since the louvers are horizontal, a view straight out is maintained while the higher sun is blocked and turned into electricity. The partially opaque type of PV glazing is created by applying opaque PV cells to the glazing. The spacing between cells will determine how much light will be transmitted (Fig. 8.11b). PV glazing has the potential to be an important source of electricity because of the current popularity of buildings that are mostly glass.



Figure 8.11a Semitransparent PV glazing is used as skylight glazing in the APS factory in Fairfield, California. (Courtesy of Kiss & Cathcart, architects. © Richard Barnes, photographer.)



Figure 8.11b Opaque PV cells are mounted on clear glass. The spacing between cells determines the degree of shading. As seen from below, the entranceway canopy of the Aquatic Center at the Georgia Institute of Technology is roofed with a 4.5-kilowatt array of Solarex PowerWall MSX-240/AC laminates. With their integrated inverters, these laminates provide grid-synchronized AC power. They use an optional clear Tedlar backing material that emphasizes the precision of solar cell placement and provides soft, natural lighting under the canopy. (Courtesy of and © BP Solarex.)



Figure 8.12a This close-up of the Center for Environmental Sciences and Technology Management (CESTM), State University of New York (SUNY), Albany, clearly shows the tilt of the PV shading devices. (Courtesy of Kawneer Company, Inc., © Gordon H. Schenck Jr., 1996, photographer.)



Figure 8.12b Automobile shading structures covered with PV are also ideal charging stations for electric cars. (Courtesy of the Sacramento Municipal Utility District.)

8.12 PV SHADING DEVICES

Shading devices are a very good application for PV because they can be designed to be tilted at the optimum angle (Fig. 8.12a). Shading devices can either be opaque or use PV glazing with a wide range of transparency.

PV shading structures for parked cars in hot climates are an opportunity to generate large amounts of electricity because of the huge land area devoted to parking (Fig. 8.12b). As electric cars become more common, these structures will serve as ideal charging stations.

8.13 PV: PART OF THE SECOND TIER

It is important to understand that electrical generation by PV is part of the second tier of the three-tier approach to environmental design (Fig. 8.13). The first tier consists of utilizing efficient electrical appliances, lighting systems, and air-conditioning systems to minimize the electrical load. The second tier consists of load avoidance by using PV to generate clean, sustainable electricity. The third tier consists of utilizing a full powered generator or the electrical grid to supply the small amount of electrical power and energy still required.

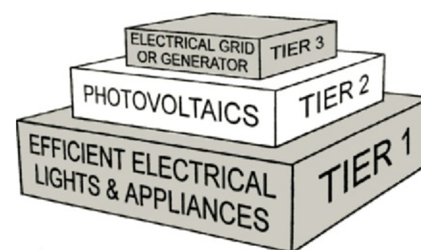


Figure 8.13 As always, the three-tier approach is a logical and sustainable strategy for environmental design.

8.14 SIZING A PV SYSTEM

Grid-connected systems are sized differently from stand-alone systems. For stand-alone systems, sizing is critical because too large a system is a very expensive waste. As mentioned above, the three-tier approach to design should be utilized to minimize the

electrical load. Furthermore, the two very large users of low-grade energy, which are space heating and domestic hot water, should not be supplied by the PV. Passive solar is the best choice for space heating, and active solar is the best choice for domestic hot water for either PV system.

For stand-alone systems, there should be backup power from an engine generator or a reliable source of wind power; otherwise, the PV system would have to be significantly larger in order to store power for extended periods of bad weather. The resultant cost would be unnecessarily high.

Table 8.14 Approximate Method for Sizing Stand-Alone Systems*

Building Type	Climate*	Array Size† (ft^2)	(m^2)	Battery storage‡ (ft^2)	(m^2)
Small residence	Mild and sunny	50	4.5	10	0.9
	Cold and cloudy	100	9	20	1.8
	Hot and humid	100	9	20	1.8
Average residence	Mild and sunny	100	9	20	1.8
	Cold and cloudy	500	45	100	9
	Hot and humid	500	45	100	9
Large residence	Mild and sunny	500	45	100	9
	Cold and cloudy	1,000	90	200	18
	Hot and humid	1,000	90	200	18

*Hot and humid climates need a large array because of the air-conditioner load. In cold and cloudy climates, the large array is due to the combined effect of lighting long winter nights and short cloudy days for generating power.

†The size of the array is very approximate in part because of the large variance in cell efficiency.

‡A space with this floor area will also contain the BOS, which includes the controller, inverter, switches, and circuit breakers.

Sizing of a Stand-Alone System

The following guidelines are for stand-alone systems with a backup power source occasionally used. Use the rules of thumb presented in Table 8.14 for a first approximation, and use the calculations in the next section for a more precise estimate.

It is critical to consider winter conditions when designing a PV system in northern regions because the lights are on for many hours, and the PV array sees the sun for few hours. In southern regions, winter design is less critical because there are more hours of daylight. Because summer air-conditioning is so common in hot regions, peak electrical loads usually occur in the summer.

Sizing a Grid-Connected PV System

There is no limit to the desired array area since the grid can use all the power produced at peak times in most areas of the United States. The cost of the array is the main determinant of size. Because the present cost of PV is high, only the orientations that can generate the most power should be used. As PV prices decline, more and more building surfaces can be clad in PV. In homes, half the roof area might be all that is needed, but in commercial, institutional, and industrial buildings, the walls, roofs, and glazing will also be put to work generating electricity. Section 8.16 will discuss the efficiency of different orientations. However, since much of the U.S. electrical demand peaks on hot, sunny summer days, most grid-connected PV systems should also peak at that time.

One likely possibility is that the power companies will rent roof space from the user in order to generate the power where it is needed. This will enable the utility to avoid the great expense of upgrading the distribution system. This is already the case with the Sacramento Municipal Utility District (SMUD) in California. More than ninety electric utilities have formed the Utility Photovoltaics Group to promote and sponsor PV installations on or around buildings.

To prevent the future problem of collectors being added at unattractive odd angles, new buildings should be oriented so that their sloped roofs face in a southerly direction close to the optimum tilt. From now on, all buildings should use or anticipate PV!

8.15 FINDING THE PV ARRAY SIZE FOR A STAND-ALONE BUILDING BY THE SHORT CALCULATION METHOD

The size of the PV array depends on the following factors:

1. Amount of electrical energy needed per day (KWH/day)
2. System efficiency—losses in inverters, controllers, etc. (50 percent is typical)
3. Amount of solar radiation available per day (KWH/ft^2/day)
4. Power produced by the PV module (KW/ft^2)

Steps for Sizing a PV Array

1. Use Form 8.15 and Table 8.15 to determine the electrical load per day in watt-hours per day.

$$WH / day = (___)$$

2. Find the adjusted load by multiplying the WH/day (Step 1) by 1.5 to account for system losses.

$$(WH / day) \times 1.5 = (___)$$

3. Determine the solar energy available at the site for one day in terms of "sun-hours" from the map in Figure 8.15a for winter-peaking loads, and Figure 8.15b for summer-peaking loads.

$$\text{sun-hours} = (___)$$

4. To find the required peak-watts (W_p), divide the adjusted load (Step 2) by the sun-hours (Step 3).

$$W_p = \frac{\text{adjusted (WH/day)}}{\text{sun-hours}} = (___)$$

5. Find the array size by dividing W_p (Step 4) by
   12 W/ft^2 for single-crystal silicon cells
   or 10 W/ft^2 for polycrystalline silicon cells
   or 6 W/ft^2 for amorphous silicon or thin-film cells
   or 5 W/ft^2 for PV standing-seam roof
   or 3 W/ft^2 for PV shingles.

$$A = \frac{W_p}{W/ft^2} = (___)ft^2$$

(For m^2, multiply ft^2 by 0.09.)

As might be expected, more efficient cells cost more. Less efficient cells sometimes give more watts per dollar, and the roof area of most residences is more than adequate to use low-efficiency cells and still generate all the power needed, especially if the roof faces south at the appropriate tilt angle.

Form 8.15 Worksheet for Determining the Electrical Load

Appliances	Watts*	Number of Hours Used Per Day	Watt-Hours Per Day
Lights			
Refrigerator†			
Washing machine			
Furnace blower			
Air conditioner			
Exhaust fans			
Television			
Computer			
Miscellaneous plug loads			
Other			
		Total Watt-Hours Per Day_________	

*Find actual watts from appliances to be used or refer to Table 8.15.
†Because refrigerators cycle on and off, they typically run about six hours per day.

Example:

Find the array size for a stand-alone residence located in the middle of Pennsylvania (40° N latitude). The total load in watt-hours per day is 3000, and the roof is made of a standing-seam PV material facing south at a tilt angle of 55° (latitude plus 15° for winter peaking).

Step 1. Use the given load: 3000 WH/day.
Step 2. Find the adjusted load by multiplying by 1.5: 3000 × 1.5 = 4500 WH/day
Step 3. Determine the sun-hours by using Figure 8.15a (for this northern location, the sun-hours = 2).
Step 4. Find the peak-watts (W_p) by dividing the adjusted load by the sun-hours: 4500/2 = 2250 W_p

Table 8.15 Typical Appliance Wattage

Device	Wattage
Incandescent lights* (wattage of lamps)	—
Fluorescent lamps (wattage of lamps plus 10% for ballast)	—
Coffeepot	200
Microwave	1000
Dishwasher	1300
Washing machine	500
Vacuum cleaner	500
Clothes dryer (uses gas)	350
Furnace blower	500
Air conditioner (central)	3000
Ceiling fan	30
Computer and printer	200
Television and DVR	200
Stereo	20
Refrigerator—conventional	500
Refrigerator—high efficiency	200

*Avoid the use of incandescent lamps and minimize the use of halogen lamps (see Chapter 14).

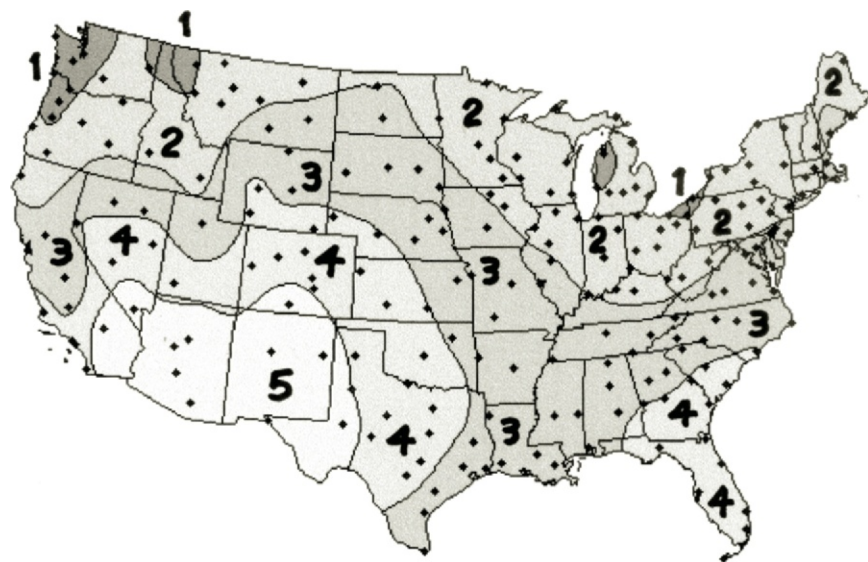


Figure 8.15a The average December solar radiation in sun-hours for a surface with a tilt equal to latitude plus 15°. Because December has the least sunshine, it is usually used for sizing PV systems. (From the National Renewable Energy Laboratory–NREL.)



Figure 8.15b The average July solar radiation in sun-hours for a surface with a tilt equal to latitude minus 15°. (From the National Renewable Energy Laboratory–NREL.)

Step 5. Since a standing-seam roof is specified, divide W_p by 5 W/ft² to find the area of the array: 2250/5 = 450 ft² (450 ft² × 0.09 = 40.5 m²)

8.16 DESIGN GUIDELINES

Use the following guidelines to get the full benefits of the PV system sized with the methods described above:

1. Consider using BIPV to save money and improve the aesthetics.
2. Use the following orientations and slopes in descending order of efficiency (most efficient first).
   a. Roof with a southerly orientation tilted at (see Fig. 8.16):
      - latitude for maximum annual energy production
      - latitude − 15° for summer peaking
      - latitude + 15° for winter peaking

   b. South wall
   c. West wall
   d. East wall

   Fortunately, solar performance is not degraded very much with some deviation from the optimum tilt and orientation.
3. Make sure the array is not shaded or shaded as little as possible. Avoid having even a small area of array shaded because of the "Christmas-lights-in-series-syndrome," where if one light goes out, all the lights go out.
4. Keep modules cool by venting their backs (cool cells generate more electricity than hot cells), and use this heat in winter.
5. Avoid arrays that are horizontal or low-sloped since they collect dirt.
6. Mount modules at a steep tilt in snow country so that snow will quickly slide off.

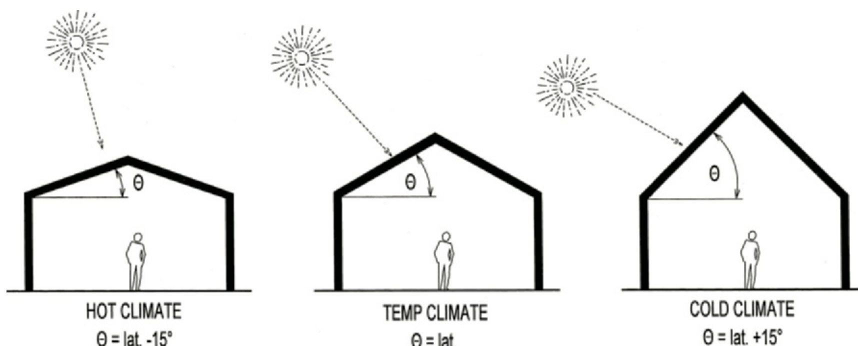


Figure 8.16 This figure shows the recommended tilt angles for PV arrays in order to maximize electricity production as a function of climate

8.17 THE PROMISE OF PV

In architecture, an elegant solution is one that has many benefits besides solving the immediate problem. Thus, a roof would be much more elegant if, besides its traditional function, it also produced all the energy the building needed. If PV replaced all of the roofing, the amount of power produced would be much more than any residence could use. Consequently, each home would be an exporter of energy, and instead of being a burden on the environment, many buildings could become environmental assets.

I remember looking out at the roofscape of New York City from a high building and thinking what a waste these thousands of empty, flat roofs were. Very few roofs were used either for gardens or for cooling-tower supports. Consider the enormous value of this resource, which is about equal to the built land area of the city. If these roofs were covered by PV, the energy would be produced right where it is needed, with minimal transmission losses (Fig. 8.17). If all roofs in the United States were covered with PV, they could produce 35 percent of all the required electricity. With the deregulation of the electric power industry, an entrepreneur could offer a building owner a free, no-maintenance, high-quality roof for the privilege of generating power. What a gigantic amount of clean, renewable power would be generated right where it is needed.

If all roofs and most south walls were covered with PV, most towns and



Figure 8.17 A 360-kilowatt array using Solarex's MSX-120 power modules mounted on the roof of an aquatic center. The installation is located on the campus of Georgia Tech University, Atlanta, the site of the 1996 Summer Olympics. (Courtesy of and © BP Solarex.)

small cities would produce all the electricity they needed. Although large cities, especially with dense clusters of high-rise buildings, could not be energy-independent, they would need to import much less power than at present. All new construction should either have BIPV or be designed to accept PV when the cost has declined further.

PV applications are not limited to the Sun Belt but are appropriate in almost all climates (see Colorplate 21). In Norway, which is as far north as Alaska, more than 50,000 vacation houses are powered solely by PV systems, and Germany, with its limited solar resource, is presently the leading user of PV in the world.

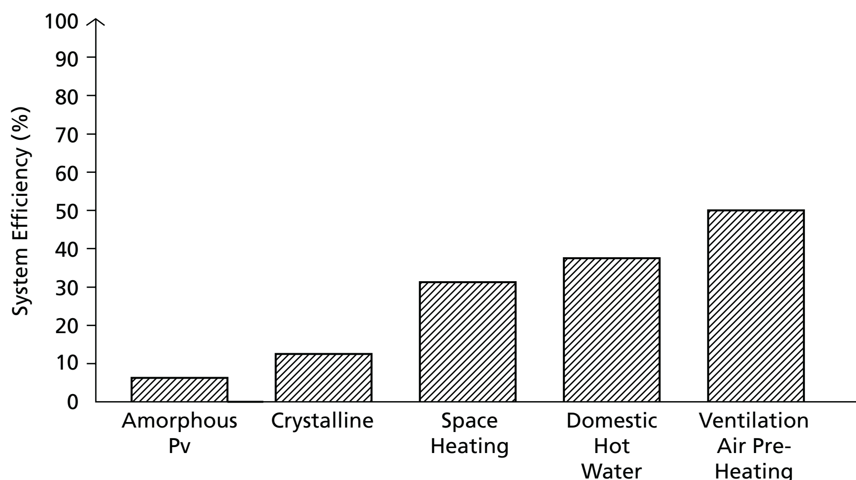


Figure 8.18a This chart shows the system efficiency of basic PV and active solar systems. The wise rule of "pick the low-hanging fruit first" suggests that with limited resources it is best to use ventilation air preheating, domestic hot water, and active solar space heating systems before using PV. Not included in this chart is passive solar, which is the most efficient way to heat a space.

8.18 THE COST-EFFECTIVENESS OF PV AND ACTIVE SOLAR APPLICATIONS

The main competitors of PV for roof space are solar collectors designed to produce hot air or water. Hot air is used primarily for space heating, while hot water can be used for a number of purposes: domestic hot water, space heating, space cooling, swimming-pool heating, and commercial hot water. Regarding the present and near-future costs of PV, it is much more economical to create hot air or water directly rather than to use PV electricity (Fig. 8.18a). Also, as was explained in Chapter 3, it is not sensible to convert a high-grade energy, such as electricity, directly into a low-grade energy, such as heat.

The most sustainable way to meet a building's need for hot air and water can be understood by the three-tier design approach (Fig. 8.18b). Tier one consists of minimizing the needs through efficiency. In the second tier, active collectors harvest the sun. Only in the third tier will mechanical systems using nonrenewable energies be called upon to supply the small load that remains after tiers one and two.

The term "active solar" is used to designate mechanical devices whose sole purpose is to collect solar energy in the form of heat and store it for later use. The working fluid is sometimes air, but usually it is water to transport the heat from the collector to the storage tank. This equipment is referred to as active solar because it must have a pump or blower. It is important to note that this equipment

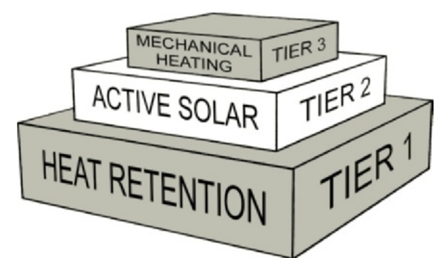


Figure 8.18b A building's hot-air and water needs are best provided by tier two of the three-tier design approach.

does just one thing: collect heat. On the other hand, a passive system, as discussed in the previous chapter, uses only the basic building fabric to collect the heat (Fig. 8.18c). Since the building fabric is there anyway, passive solar is free or nearly so. Furthermore, since there are no mechanical parts to break or wear out, passive solar is more reliable and requires little or no maintenance. Thus, it is generally agreed that passive solar is the best choice for space heating wherever there is access to the sun. It won't work, for example, if only the roof of a building has access to the winter sun. In that case, active solar space heating might be appropriate. Solar access is often a problem in urban areas, in wooded sites (especially if evergreen), and in high latitudes where the very low winter sun in easily blocked. Thus, active solar is sometimes used for space heating, but mostly it is used for heating water for other purposes (Fig. 8.18d).

Five different applications exist for hot water in buildings: swimming-pool heating, domestic hot water, commercial/institutional hot water, space heating, and solar cooling. Buildings such as hospitals, apartment buildings, schools, jails, car washes, nursing homes, health clubs, restaurants, and hotels all use large quantities of hot water that can be produced economically by an active solar system. See Table 8.18 for the relative cost effectiveness of these different applications.

Heating swimming pools with solar energy is very cost effective for several reasons. Firstly, outdoor pools are heated only in the spring, summer, and fall (to extend the swimming season) when much more solar energy is available than in the winter. The second reason is based on the laws of thermodynamics: all solar collectors have the highest efficiency at their lowest operating temperature. Since pool-water temperatures are rather low (about 80°F [26°C]), the efficiency of the solar collectors is very high (Fig. 8.18e). And thirdly, the equipment needed for the solar heating of swimming pools is relatively inexpensive.

This low-temperature efficiency also applies to two forms of space heating. A radiant floor heating system can make good use of water heated to only 90°F (32°C), or a heat pump can **upgrade** the heat that solar collectors gather. Heat pumps will be explained in Chapter 16.

Domestic hot water is also a good application for active solar, but for a different reason. Since domestic hot water is required year-round, the equipment is never idle. This, unfortunately, is not true for space heating. Not only is an active solar space-heating system idle for much of the year, but when it does work in the winter, the supply of solar energy is at its

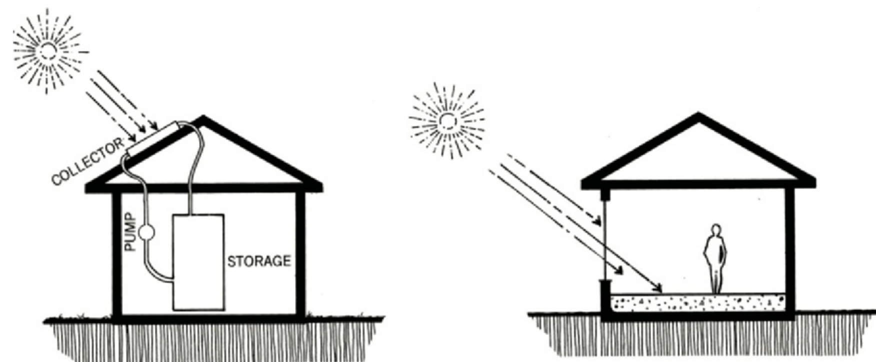


Figure 8.18c Active solar systems require specialized mechanical equipment to work, while passive solar relies only on existing elements of the building fabric. Consequently, passive solar is less expensive for space heating in most cases.



Figure 8.18d Active solar hot-water heaters should be on every building, as they are in the development called Pacifica in Carrboro, North Carolina.

Table 8.18 Cost Effectiveness of Various Active Solar Applications

Application	Economical?
Swimming-pool heating	Yes, (two- to three-year payback)
Domestic hot water	Yes (five- to eight-year payback)
Active space heating	Sometimes (rarely in the South, frequently in cold northern climates when passive solar is not possible)
Solar space cooling or dehumidification	Sometimes (long payback period at present)
Process hot water	Usually

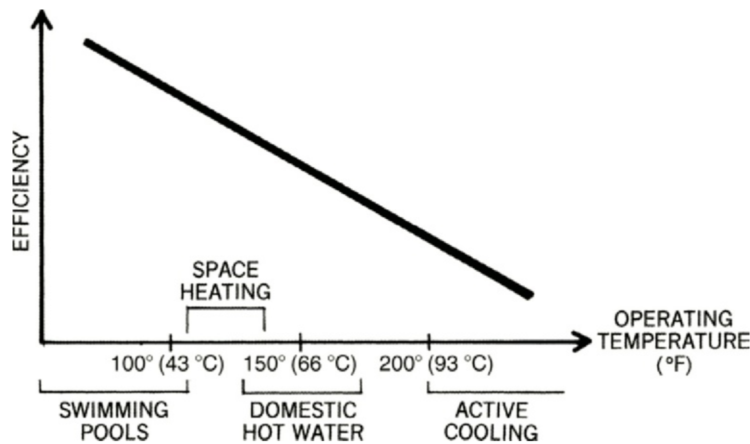


Figure 8.18e The performance of a typical flat-plate solar collector is shown. Although the exact curve varies with the collector type, the efficiency always declines with an increase in the collection temperature. Note the relationship between temperature and application.

Climax Solar-Water Heater
UTILIZING ONE OF NATURE'S GENEROUS FORCES
THE SUN'S HEAT { Stored up in Hot Water for Baths, Domestic and other Purposes.
GIVES HOT WATER at all HOURS OF THE DAY AND NIGHT.
NO DELAY.
FLOWS INSTANTLY.
NO CARE. NO WORRY.
ALWAYS CHARGED.
ALWAYS READY.
THE WATER AT TIMES ALMOST BOILS.
Price, No. 1, $25.00
This Size will Supply sufficient for 3 to 8 Baths.
CLARENCE M. KEMP, BALTIMORE, MD.
OUTLET
INLET
Price Of No.1 Heater for 1892 Reduced to $15 Net

Figure 8.18f This advertisement for a solar hot-water heater appeared in 1892. (From Special Collections, Romaine Collection, University of California, Santa Barbara; cited in *A Golden Thread*, by Ken Butti and John Perlin.)

lowest point. Consequently, active systems for space heating are less efficient than they are for domestic hot water or swimming-pool heating. However, an important exception exists. Preheating ventilation air in cold climates can be accomplished very economically with transpired collectors, which will be discussed in Section 8.24.

Limitations on active solar systems are more economic than technical. Where cheap alternative energy sources are not available, solar energy is popular. Active solar systems are common in many countries—millions of systems are now operating in Europe, Asia, and the Middle East. China is now the largest producer, user, and exporter of active solar systems in the world. Ironically, active solar systems were sold in the United States at the turn of the twentieth century and became quite popular in Florida and Southern California (Fig 8.18f). By 1941, about 60,000 solar hot-water systems existed in the United States. Solar energy declined after that time, not because it did not work but because fossil energy was cheaper and solar was no longer fashionable. Because only the poor kept their solar rooftop systems, the public developed a negative image of solar energy.

About 20 percent of the residential energy consumption in the United States is for domestic hot water. Because heating hot water is a substantial use of energy, it should not be heated by energy derived from fossil fuels. The best way to heat hot water is with a solar collector.

Because solar swimming-pool heaters are the most cost-effective and simplest of the active solar systems, they are described first.

8.19 ACTIVE SOLAR SWIMMING-POOL HEATING

As mentioned before, solar swimming-pool heaters are very cost-effective because they collect the sun during the part of the year when solar energy is plentiful and because they collect heat at rather low temperatures. At these relatively low temperatures, the collectors are not only very efficient but can also be rather simple and inexpensive to manufacture (Fig. 8.19a). The rest of the system is also inexpensive because the existing filtration equipment can often be used to circulate the water (Fig. 8.19b). And unlike other active solar heaters, freeze protection is not needed because the systems are not used in the winter.

As with buildings, the first step in heating a pool is to reduce heat loss. Since most of the heat is lost by evaporation, a pool cover is a must. The above discussion refers to outdoor pools. For indoor pools that can be used year-round, active solar systems similar to the kinds used for domestic hot water described below are required.

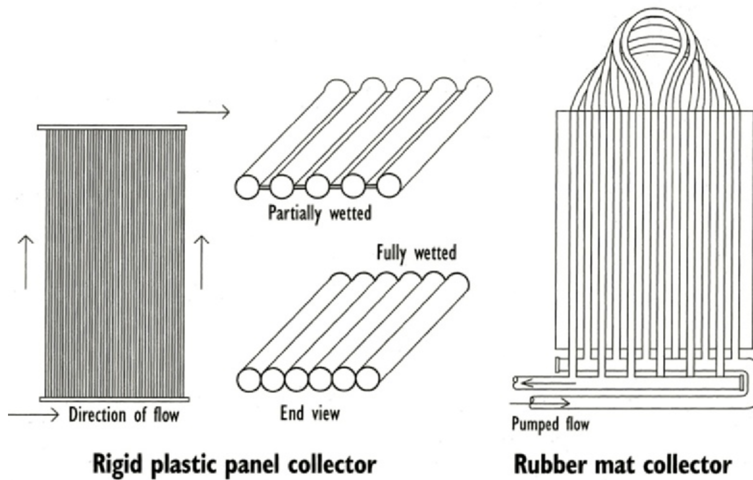


Figure 8.19a Solar swimming-pool collectors are simple and inexpensive because they need neither glass covers nor insulation. Some are made of flexible extruded plastic that can be shipped in a roll. (Courtesy of Dan Cuoshi, © *Home Energy Magazine*.)

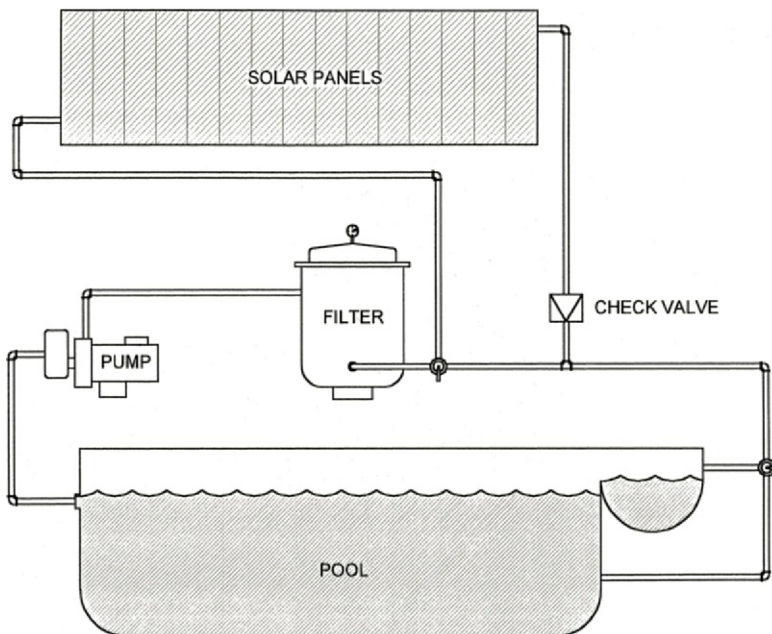


Figure 8.19b Outdoor swimming-pool heating systems often use their existing filtration equipment to circulate the water. (After Sun Trapper Solar System Inc.)

Rules of Thumb for Sizing Swimming-Pool Collectors*

1. For the hot southern United States, use a collector area equal to 50 percent of the pool area.
2. For the cold northern United States, use a collector area equal to the pool area.
3. For states in the middle, use a collector area equal to 75 percent of the pool area.

*These values are for orientation within 20° of south and a tilt angle near (latitude –15°). For only fair orientation and tilt, add 25 percent, and for poor orientation and tilt, add 50 percent additional collector area.

8.20 SOLAR HOT-WATER SYSTEMS

Since most buildings need domestic hot water, most active systems use water rather than air as a heat-transfer-and-storage medium. Such water-based systems can also be easily used for space heating. Each system must have a collector, heat-transfer fluid, and a storage device. To protect against freezing and boiling, some water systems use a mixture of water and antifreeze. An insulated tank, usually located indoors, stores the hot water. The collector must be more sophisticated than the swimming-pool kind because it has to generate medium-high temperatures (120° to 140°F [50° to 60°C]) even on very cold winter days.

The most common kind of collector used for producing domestic hot water is called a **flat-plate collector**, which essentially consists of a metal plate coated with a black **selective surface** to reduce heat loss by reradiation (see Section 3.11). A glass cover creates the greenhouse effect to maximize the energy collected, and insulation is used to reduce heat loss from the back and sides of the collector (Fig. 8.20a). Water is pumped through pipes attached to the hot collector plate, and the heated water is then stored in tanks located inside the building. To prevent contamination of the potable domestic hot water, a heat exchanger is used.

When the controller senses that the water is warmer in the collector than in the storage tank, the pump is activated, and when the sun sets and the collector is cooler than the storage tank, the controller shuts off the pump. In a particular arrangement called a **drain-back system**, the water completely drains into the indoor tank whenever the pump does not operate (Fig. 8.20b). Consequently, water will never freeze or boil in the collector and antifreeze is not needed. Other system designs are used, depending on the climate and the

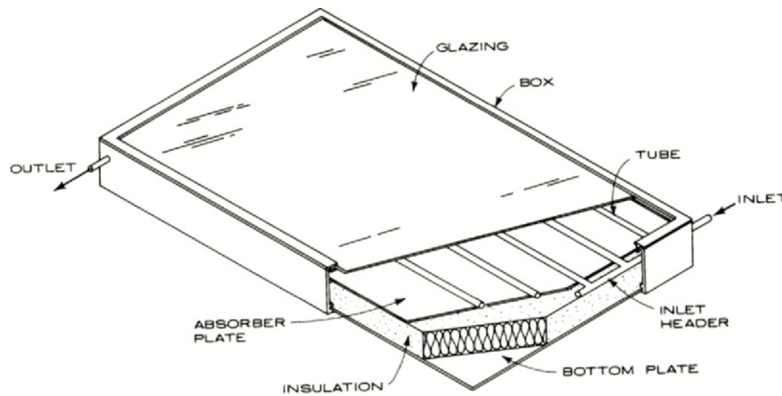


Figure 8.20a A typical flat-plate collector designed to heat a liquid. (From *Architectural Graphic Standards, Ramsey/Sleeper*, 8th ed., John R. Hoke, editor © John Wiley & Sons, Inc., 1988.)

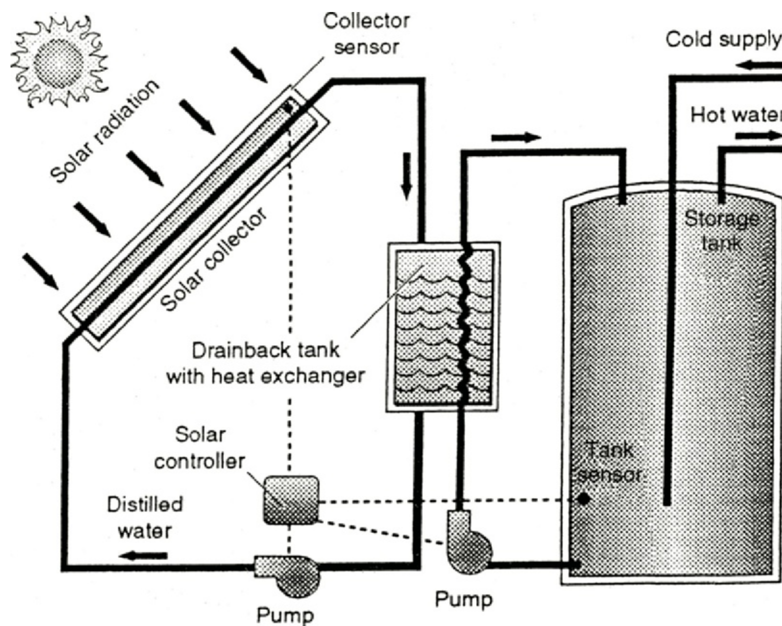


Figure 8.20b The drain-back solar hot-water system is shown. To prevent contamination of the domestic hot water, a heat exchanger is used. A space-heating system can also utilize the hot water in the tank. (From the Texas State Energy Conservation Office, Fact Sheet #10.)

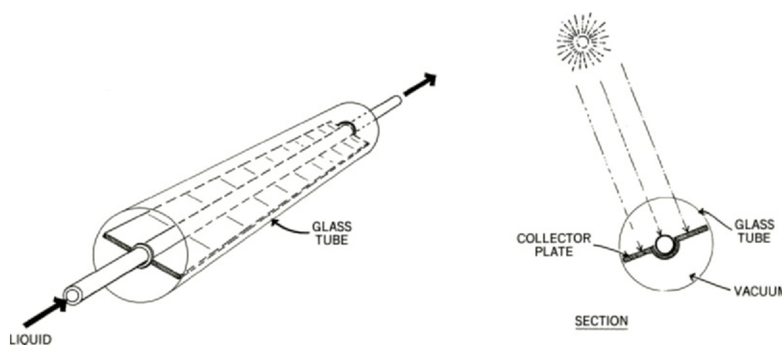


Figure 8.20c A vacuum-tube collector achieves high temperatures by reducing heat loss. All convective and most conductive losses are eliminated by the vacuum, and most radiant losses are eliminated by a selective coating.

particular company that makes the system.

An alternative to the flat-plate collector is the evacuated or vacuum-tub solar collector, which is almost universally used in China because of its very high efficiency and resistance to freezing (Fig. 8.20c). If heat pipes are used inside the evacuated tube, then the tubes must be used in an inclined position (Fig. 8.20d). On the other hand, if water is circulated through the vacuum tubes, they can be used in any position. They have even been used as a balcony railing (Fig. 8.20e). The tubes are 2 to 4 in. (5 to 10 cm) in diameter, and they come in many lengths.

Space heating with hot water is also called hydronic heating and is discussed in Section 16.6. The radiant floor heating system that circulates hot water through the floor is a good match with active solar, because it can use water at a relatively low temperature, which makes the collection more efficient (see again Fig. 8.18e).

Use concentrating solar collectors for generating either high temperature process water or to power an absorption air conditioner. The most common concentrating collector consists of a tracking linear parabolic mirror to focus the sun on a pipe containing a liquid with a very high boiling point (Fig. 8.20f).

To make it unnecessary to have both PV and active solar panels on the roof, one company has made a sandwich where water is used to both cool the PV and collect heat for the building (Fig. 8.20g).

It is not practical to try to design a 100 percent solar system, because sunshine is irregular. It would take a very large solar collector and storage system to supply hot water after a week of cloudy, cold weather. Since such a large system would be completely overdesigned for most of the year, the overall efficiency would be low. Thus, a 100 percent solar heating system is not economical; the optimum percentage varies with the climate but is usually between 60

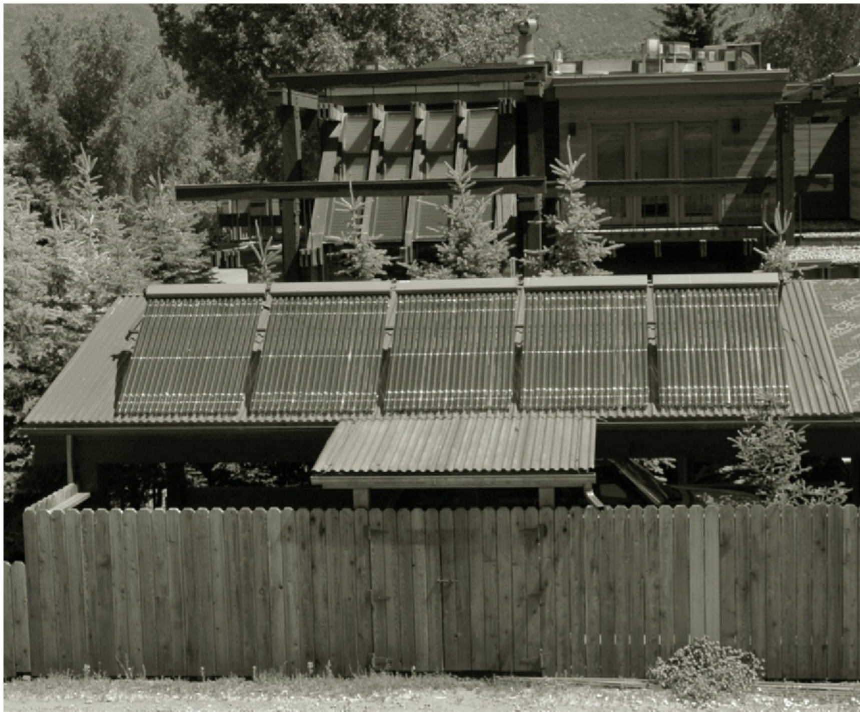


Figure 8.20d Vacuum-tube solar collectors can produce very hot water efficiently. They can also be an attractive visual element, as seen in these townhouses in Aspen, Colorado.

and 80 percent. Consequently, the collector area needed is rather modest, with most homes using only one or two panels for domestic hot water.

8.21 SOLAR HOT-AIR COLLECTORS

Hot-air collectors are used primarily for space heating. The main disadvantages of air as a collecting fluid are: much fan power is needed because of the low heat capacity of air, the collectors and ducts are bulky, it is hard to prevent air leakage, and it is inefficient to heat domestic hot water with the hot air. The advantages are: air doesn't freeze or boil, leaks don't cause damage, and the warm air can be used directly to heat the building. Early systems usually stored the heat in a rock bin (Fig. 8.21a). However, it is usually

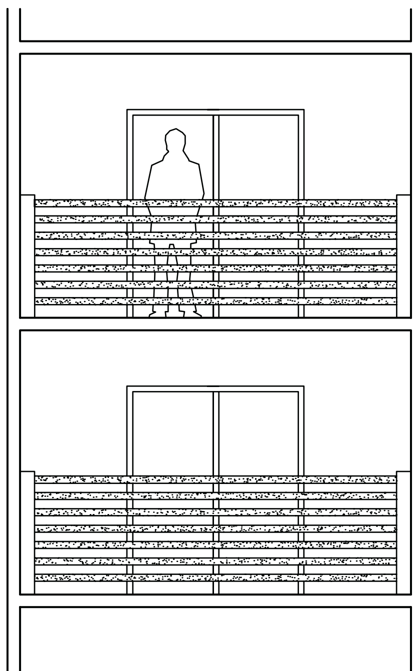


Figure 8.20e In multistory buildings in northern latitudes, the solar collectors can be mounted vertically on south-facing facades. Here vacuum-tube collectors are used as a balcony railing.

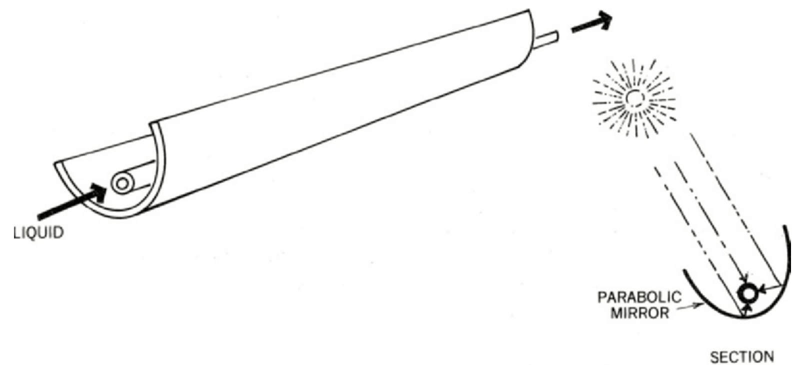


Figure 8.20f Because a concentrating collector uses a parabolic mirror to achieve high temperatures, it must track the sun.

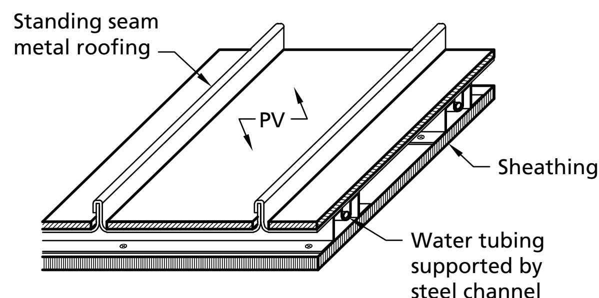


Figure 8.20g This sandwich panel generates both electricity and hot water. The Englert company produces such a panel.

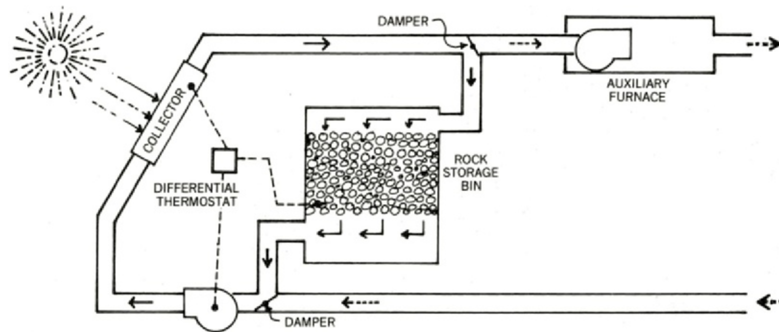


Figure 8.21a Many early solar hot-air systems for space heating used a rock bin to store the heat for nighttime use. The dampers are shown in their position for daytime heat storage (After *Architectural Graphic Standards*).

more economical to use the mass of the building, as in the popular Japanese system described in Figures 8.21b through 8.21f.

A very simple and cost-effective hot-air system consists of vertical flat-plate collectors attached to the south facade (Fig. 8.21g). Two small holes through the south wall allow a small fan to circulate room air through the collector for daytime heat without additional sunlight entering the space.



Figure 8.21b One popular active solar system in Japan uses special hot-air collectors to gather the heat and concrete floor slabs to store the heat. The collectors cover the whole roof, but for economic reasons, only the upper third is covered with glass. This system is used in homes, schools, and small community buildings. (After Oku Mura of the OM Solar Association/OM Institute.)

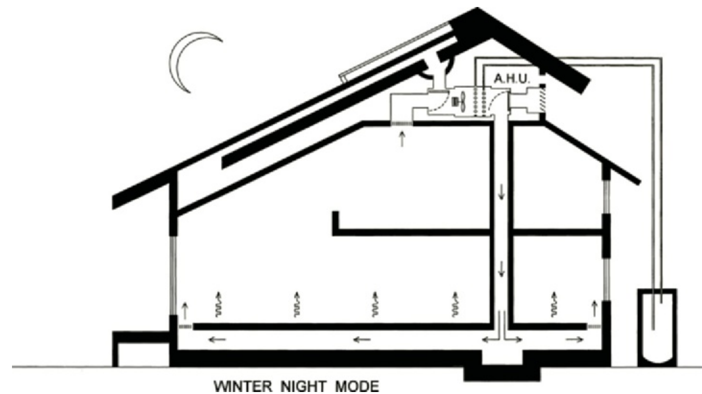


Figure 8.21d Winter Night Mode: When necessary, an auxiliary heating coil in the air-handling unit supplements the heat stored in the slab. (After Oku Mura of the OM Solar Association/OM Institute.)

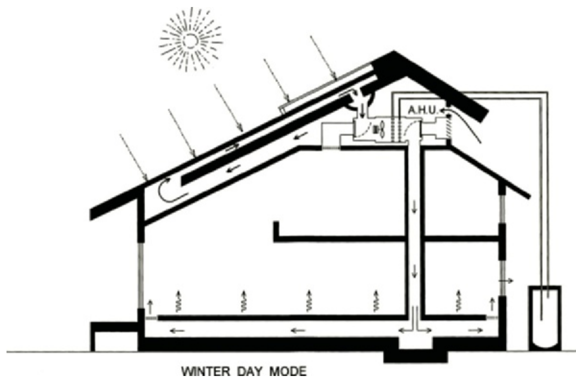


Figure 8.21c Winter Day Mode: Fresh outdoor air entering through attic vents is first preheated by the unglazed portion of the metal roof and then fully heated by the more efficient glazed section. The air-handling unit then blows the air under the floor slab to heat the perimeter of the building while it also stores heat in the slab. (After Oku Mura of the OM Solar Association/OM Institute.)

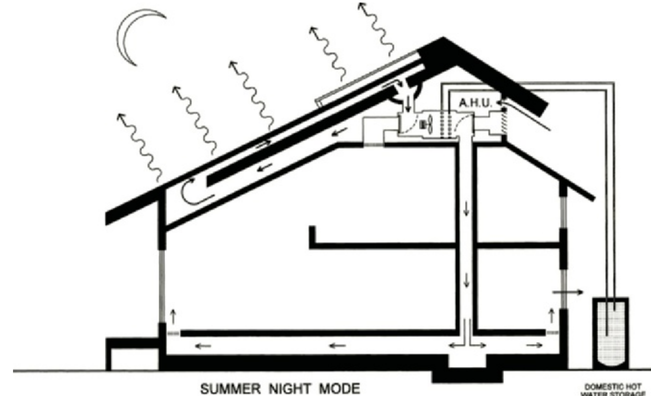


Figure 8.21e Summer Night Mode: Outdoor air is cooled by passing through the metal roof collectors that radiate heat to the night sky. The cooled air then cools the floor slab and interior spaces in preparation for the next hot day. (After Oku Mura of the OM Solar Association/OM Institute.)

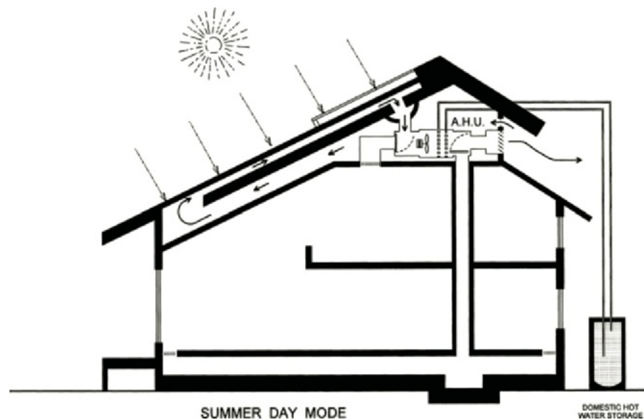


Figure 8.21f Summer Day Mode: As in the winter, outdoor air is passed through the collectors, but now the heat is transferred into a domestic hot-water coil and then exhausted outdoors. In the process, the roof and attic are cooled by the flow of this outdoor air. Note that the attic vents and exhaust louvers from the air-handling unit are widely separated horizontally. (After Oku Mura of the Om Solar Assoc./Om Institute.)



Figure 8.21g Simple and inexpensive hot-air collectors can be added to the south wall of new or existing buildings for additional daytime solar heating. (Courtesy of Sun Mate.)

8.22 DESIGNING AN ACTIVE SOLAR SYSTEM

Because of the expense of solar equipment, the system must be designed to be as efficient as possible. It is most important to maximize the solar exposure by aiming the collectors at the sun and by minimizing the shading of a collector while it gathers energy from about 9 A.M. to 3 P.M. In most cases, rooftops have the best solar access (Figs. 8.22a and 8.22b). Rooftop mounting also saves land and minimizes the potential for damage that exists with ground-mounted collectors. A study model on a heliodon is the most effective way to check for solar access when there are many possible obstructions. See Chapter 11 for a discussion on solar access.

Collector Orientation

Usually it is best to orient solar collectors toward true south. Variations up to 20° east or 20° west are acceptable (Fig. 8.22c). For special conditions, such as a need for morning heat or the prevalence of morning fog, a 20° to 30° shift to the east or west can even be beneficial.

Collector Tilt

The **optimum tilt** of the collectors is a function of latitude and the purpose of the solar collectors. Figure 8.22d illustrates the tilt angle for different heating applications as a function of latitude and the purpose of the collector. Collectors are most efficient when they are perpendicular to the sunrays. However, with the daily and seasonal motions of the sun, that is possible only with tracking collectors, which are not practical for active solar collectors in most circumstances. Thus, the tilt angles given in Figure 8.22d are the optimum slopes for different functions.

Quality Control

Only solar systems that are certified by the Solar Rating and Certification Corporation or other credible testing organization should be specified. This organization has testing laboratories in the United States and all over the world.

Collector Size

The collector size depends on a number of factors: type of heating (pool water, domestic water, or space



Figure 8.22a This add-on to an existing building consists of two flat-plate collectors for domestic hot water. There is also a special low-temperature swimming-pool collector made of flexible plastic that is draped over the roof tiles (upper right.)



Figure 8.22b The active solar collectors are an integral part of this roof design. (Courtesy of and © Chromagen-Solar Energy Systems, Israel.)

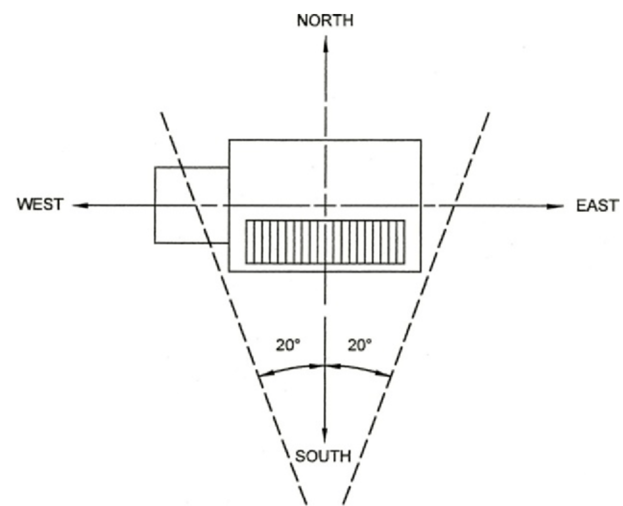


Figure 8.22c Although due south is usually the best orientation for collecting solar energy, the losses are quite small if the deviation is less than 20°.

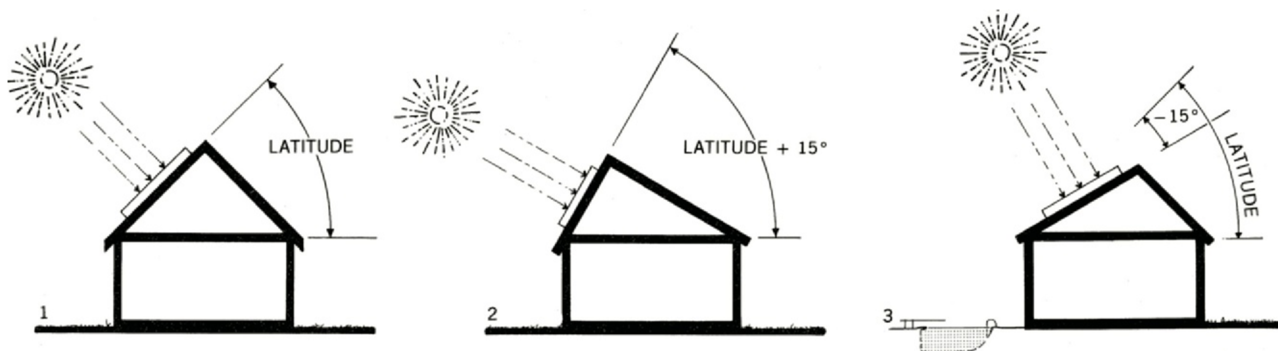


Figure 8.22d The best collector tilt is a function of latitude and the purpose of the collector: (1) a collector tilt for domestic hot water; (2) a collector tilt for space heating and for the combination space heating and domestic hot water; (3) a collector tilt for heating swimming pools or for solar cooling.

Table 8.22A Approximate Sizing of a Solar Domestic Hot-Water System*

Number of People per Household	Approximate Collector Size (ft^2)† in Regions				Approximate Tank Size			
	A	*B*	*C*	*D*	*Gallons*	*(liters)*	*ft^3*	*(m^3)*
1–2	30	40	60	80	60	227	8	0.2
3	40	53	80	107	80	303	11	0.3
4	50	67	100	133	100	379	13	0.4
5	60	80	120	160	120	754	16	0.5
6	70	93	140	187	140	530	19	0.6

*Based on the rules of thumb and map from AAA Solar Service and Supply, Inc., Albuquerque, New Mexico.
†The collector area is also a function of its efficiency. (For m^2, multiply ft^2 by 0.09.)

Table 8.22B Approximate Sizing of a Combined Space-Heating and Domestic Hot-Water System for a 1500 ft^2 (135 m^2) Home

Climate Region	Reference City	Approximate Collector Area (ft^2)	(m^2)	Approximate Storage Size: Water (ft^3)	(m^3)	Rock Bin* (ft^3)	(m^3)
1	Hartford, CT	800	72	200	5.7	600	17
2	Madison, WI	750	68	200	5.7	600	17
3	Indianapolis, IN	800	72	200	5.7	600	17
4	Salt Lake City, UT	750	68	200	5.7	600	17
5	Ely, NE	750	68	200	5.7	600	17
6	Medford, OR	500	45	100	2.8	300	8.5
7	Fresno, CA	300	27	70	2	210	6
8	Charleston, SC	500	45	100	2.8	300	8.5
9	Little Rock, AK	500	45	100	2.8	300	8.5
10	Knoxville, TN	500	45	100	2.8	300	8.5
11	Phoenix, AZ	300	27	70	2	210	6
12	Midland, TX	200	18	40	1.1	120	3.4
13	Fort Worth, TX	200	18	40	1.1	120	3.4
14	New Orleans, LA	200	18	40	1.1	120	3.4
15	Houston, TX	200	18	40	1.1	120	3.4
16	Miami, FL	50	5	10	0.3	30	0.8
17	Los Angeles, CA	50	5	0	0	30	0.8

Sizes are approximate and vary with the actual microclimate and the efficiency of specific equipment.
*Rock bin is used with a hot-air system.

heating), amount of heat required, climate, and efficiency of the collector system. Table 8.22A gives the approximate collector areas and storage-tank sizes for domestic hot-water heating, while Table 8.22B gives the approximate sizes of collectors and storage tanks for a combined space-heating and domestic hot-water system. For sizing swimming-pool heating systems, see Section 8.19. In all cases, the collector area should be increased to compensate for a poor tilt angle, a poor orientation, or a partial shading of collectors.

8.23 ACTIVE/PASSIVE SOLAR SYSTEMS

At the end of Chapter 7, it was mentioned that although the convective-loop (thermosiphon) system (Fig. 7.18a) is a passive system because it uses no pumps, it is more closely related to active systems. The first active solar systems at the turn of the twentieth century used this natural-convection technique. Because of their simplicity and low cost, two different thermosiphon systems are becoming popular for domestic hot water. In one system, called a **batch heater**, the storage tank is also the collector (Fig. 8.23a). The more popular thermosiphon system

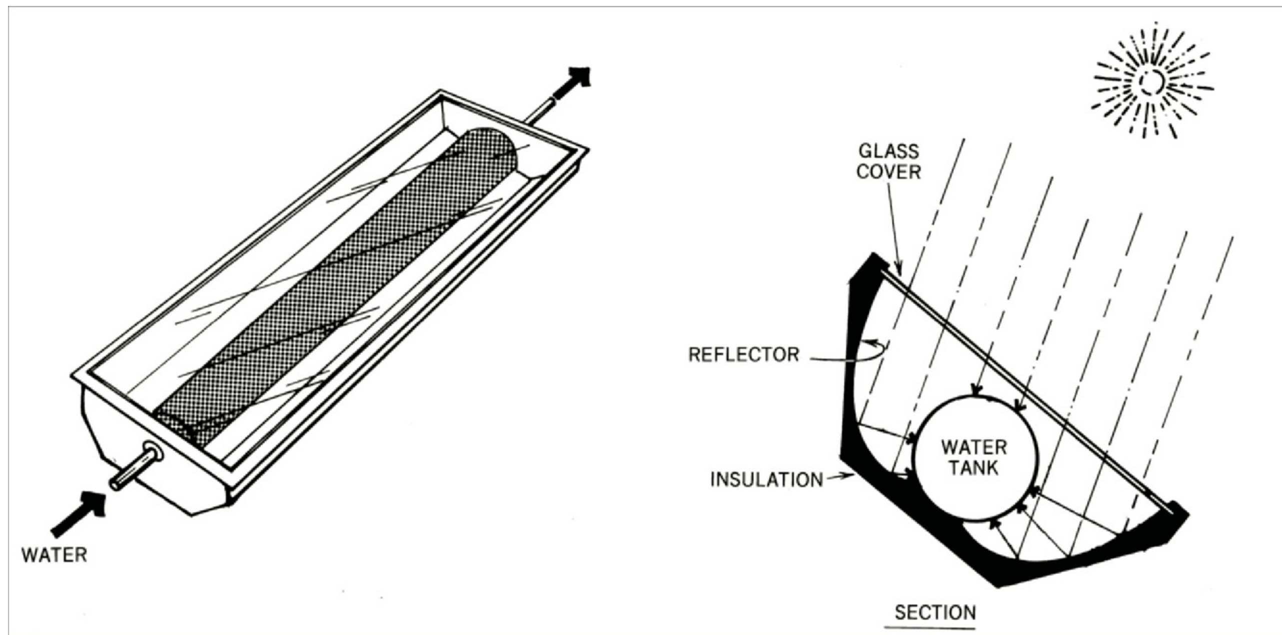


Figure 8.23a In a batch-type hot-water heater, the collector and storage are one and the same.

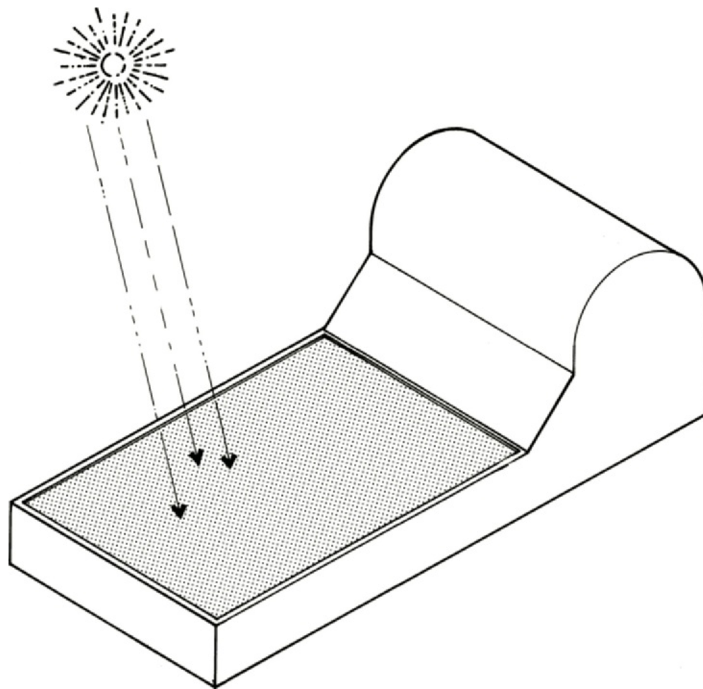


Figure 8.23b In an integral collector storage (ICS) system, the collector and storage tank are supplied in one package.

is called **the integral collector storage (ICS) system** because the storage tank and collector are combined in one unit (Fig. 8.23b). Because these systems have no moving parts and a minimum of plumbing, they are very cost-effective and popular. They are most appropriate in mild to temperate climates because the storage, although well insulated, is outdoors. For thermosiphons to work, the storage tank must be above the collector. Their major disadvantage is aesthetic since they cannot be easily integrated into the roof, while flat-plate collectors can look much like skylights.

8.24 PREHEATING OF VENTILATION AIR

As mentioned earlier, active solar swimming-pool heating is very cost-effective partly because simple, inexpensive collectors that don't use glass covers are sufficient for the low-temperature heat that is collected. Similarly, simple, inexpensive solar collectors are sufficient to preheat ventilation air because even a small rise above the winter outdoor air temperature is a benefit.

A simple ventilation preheater can be made by mounting dark metal cladding a few inches in front of a south wall. A ventilation fan moves cold outdoor air across the back of the metal cladding before the air enters the building. Unfortunately, this strategy does not capture the warm air film that forms on the front of the dark metal collector, but by perforating the cladding, heat is collected from both the front and back

of the collector, yielding efficiencies as high as 75 percent (Fig. 8.24a). Such **transpired solar collectors** even save energy at night because the heat lost through the south wall is brought back in by the incoming ventilation air. In summer, the building ventilation system bypasses the solar collector, while the air being heated inside the collector rises by the stack effect and exits through the top perforations or a damper vent. Thus, minimal heat gain results in the summer from the solar collector.

Since the collector is the facade, the collector's appearance is very important. Fortunately, any dark color will work almost as well as black. On sunny days, the air can be heated anywhere from 30° to 50°F (17° to 30°C) above the ambient temperature. Even on cloudy days, the system is still about 25 percent efficient.

All buildings need to bring in outdoor air for health reasons and odor control. Because we use materials that give off toxic components, **indoor-air quality (IAQ)** has become an important issue. Small buildings, such as residences, have traditionally relied on infiltration to supply the needed fresh air, while large buildings have relied on a designed ventilation system. Because energy-efficient buildings have an airtight envelope, all buildings now need a carefully designed ventilation system, and in winter, preheating this fresh air will save a great deal of energy. Figure 8.24b shows a high-rise apartment building that uses an active solar ventilation preheater made of perforated cladding panels. Preheating ventilation air is also appropriate for existing buildings. It is especially useful for buildings with badly deteriorated south facades, for which new cladding might be needed anyway.

Although transpired solar collectors are most useful in cold climates where much ventilation is required, such as in industrial buildings, hospitals, schools, and restaurants, they should be used by all buildings located in cold climates. For example, the National Renewable Energy

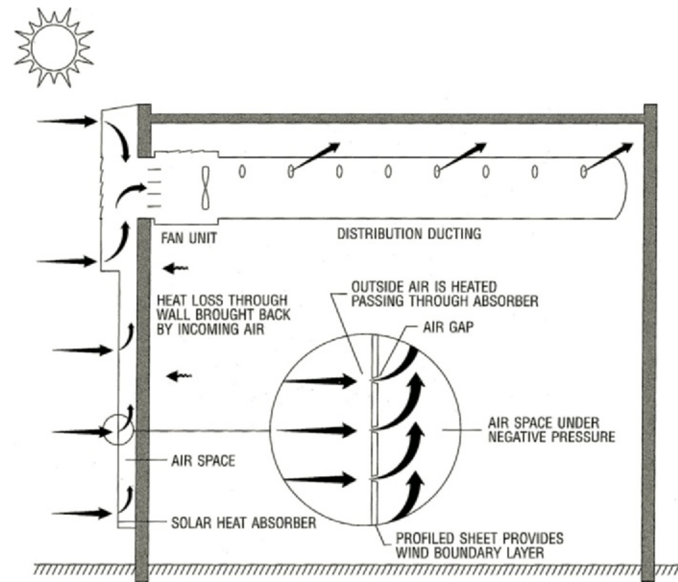


Figure 8.24a An active solar transpired ventilation preheater system is shown. Much greater efficiencies are achieved when metal collectors are perforated. (Courtesy of Conserval Systems Inc., makers of the Solarwall system.)



Figure 8.24b This Windsor, Ontario, apartment building uses the world's tallest solar collector to preheat ventilation air. (Courtesy of Conserval Systems Inc., makers of the Solarwall system.)

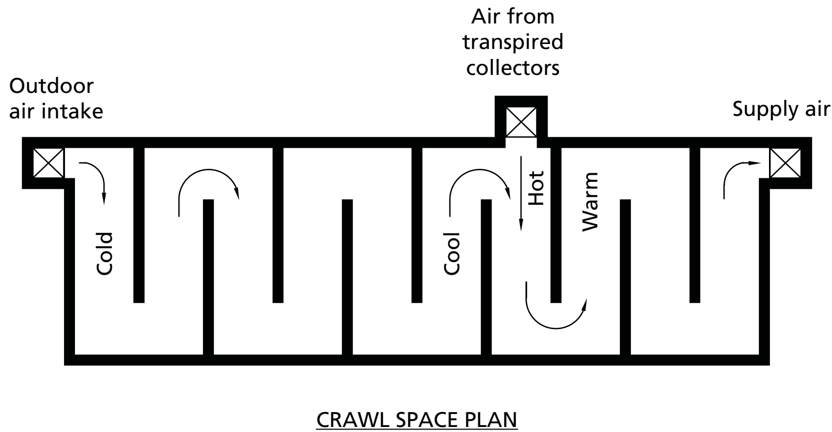


Figure 8.24c The net-zero Energy Research Support building at the National Renewable Energy Laboratory uses a crawl space labyrinth to store and preheat solar-heated ventilation air. It is also used in the summer to pre-cool ventilation air.

Laboratory Research Support building shown in Figure 8.24c uses transpired collectors on the south facade to heat the air entering the heat-storing labyrinth in the winter.

8.25 THE FUTURE OF ACTIVE SOLAR

There is no reason why 100 percent of outdoor swimming pools should not be heated with active solar, since the cost of heating pools with solar energy is easily competitive with fossil energy.

Domestic hot water should also be heated with active solar collectors unless the building has no access to the sun. Heating water is the second largest consumer of energy in homes after space heating and cooling. The term "domestic hot water," sometimes called sanitary hot water, refers to all hot water used in homes, restaurants, laundries, schools, and even car washes. However, domestic hot water does not include hot water used for heating buildings.

Domestic hot water should be heated by the sun!

Passive solar energy should be used for space heating wherever possible. When the walls and windows do not have enough exposure to the winter sun but the roof does, active solar space heating should be used. In cold climates, solar preheating of ventilation air is especially appropriate.

In hot climates, solar air-conditioning should be considered. Absorption air-conditioning can operate on solar hot water, as described in Section 16.9. The technology has existed for over twenty years and is popular in Japan. New technology, mass production, and rising energy costs may make solar air-conditioning widespread. There is much potential for solar cooling because the most cooling energy is needed at the same time of year when solar energy is most abundant.

8.26 CONCLUSION

It is now appropriate for every building to collect as much solar radiation as possible, since solar energy is a central pillar of sustainability. The threat of global warming requires us to use the sun in every form possible (Fig. 8.26a). Imagine every roof of a city covered with solar collectors. You don't have to imagine, because in Dezhou, China,



Figure 8.26a The Oxford Solar House, in Oxford, England, demonstrates solar in its many forms. The south-facing roof consists of a mix of passive solar, active solar, and PV panels. The skylight supplies daylight and direct-gain heat, the active solar supplies the domestic hot water, and the PV supplies the electricity. In addition, the south facade uses both direct-gain and sunspace passive solar. (Photo from Caddet Technical Brochure #84.)



Figure 8.26b This roofscape in Dezhou, China, is an example to the world of what is possible. Not only does every roof have solar collectors, but the buildings and streets are all aligned for the best solar orientation.



Figure 8.26c Maybe active solar hot-water heaters would be used more if they were promoted as they are in China.

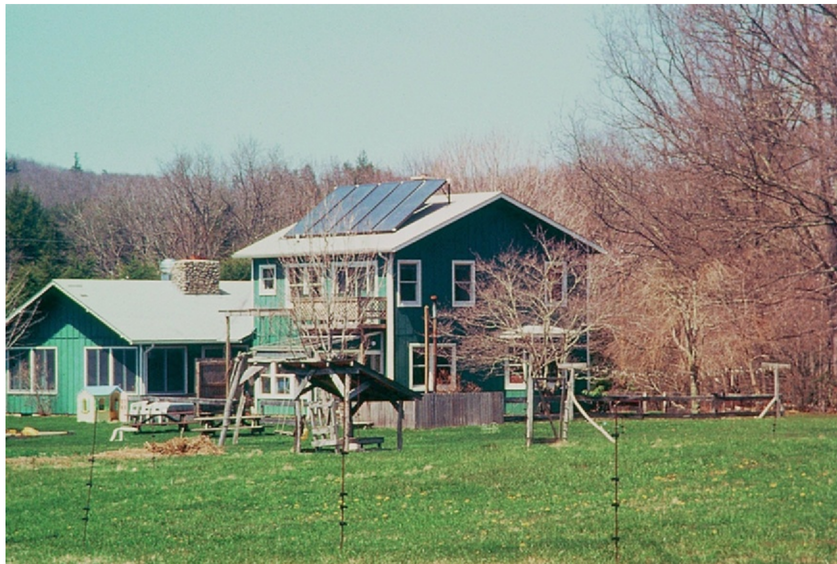


Figure 8.26d When active solar or PV is not considered in the original design, retrofit installations can prove to be very awkward.

every roof is covered with active solar collectors to supply the domestic hot water (Fig. 8.26b). Also in China, you can find stores along busy streets displaying solar collectors on the sidewalk (Fig. 8.26c).

To create a sustainable building, first use efficiency to reduce the need for energy. Second, use the passive techniques to further reduce the energy load. Next, use active solar to supply most of the low-grade heat requirements for domestic hot water and space heating. Finally, use PV to generate the high-grade energy of electricity to operate all the lights and appliances.

Because of a similarity in appearance and solar-access requirements, active solar and PV can be integrated side by side in buildings. In residences, the entire south-facing roof can be used for a combination of active solar and PV panels (see Figs. 8.3a and 8.26a). In commercial, institutional, and industrial buildings, the south wall can also be used.

It is most important that all new buildings either utilize these technologies or at the very least allow for them in the future. Thus, buildings should face south and have south-facing roofs at the appropriate tilt angle if they don't have flat roofs. Roads should be laid out to accommodate the building orientation (see Chapter 11). If these steps are not taken, many buildings in the future will have solar collectors at odd angles to the architecture (Fig. 8.26d).

Rather, the use of passive solar, active solar, and PV should generate a new aesthetic. This will be an opportunity to create new forms appropriate for a sustainable world (see Figs. 8.3b and 8.22b).

Although it is easy to see how passive, active, and PV are solar building techniques, it is not as obvious that shading is also a solar technique. Just as passive and active solar reduce the need for conventional energy in the winter, shading reduces the need for energy in the summer. Thus, rejecting the sun can be just as valuable as collecting it. The next chapter is about shading.

KEY IDEAS OF CHAPTER 8

1. Photovoltaic (PV)-generated electricity is an almost ideal energy source. PV converts sunlight directly into electricity.
2. Most of the electricity in the middle of the twenty-first century will probably come from PV.
3. PV should be building-integrated (i.e., PV modules should displace the weathering skin of a building).
4. PV is appropriate not only in the Sun Belt but in almost every climate.
5. Stand-alone PV systems are best for buildings some distance from the power grid. Such systems require batteries and backup power.
6. Grid-connected PV systems are best for buildings on or near the power grid, which replaces the need for batteries and backup power.
7. Wind power is a good complement to PV power.
8. A southern orientation and a tilt equal to the latitude maximize the annual PV output.
9. To match energy supply to demand in special cases, the optimum orientation and tilt can be off 15° to 30° from the standard orientation and tilt.
10. PV has the potential to be very inexpensive because little material is used and the assembly is highly automated.
11. As PV costs decline because of research and mass production, the optimum tilt and orientation will become less important. Someday, all south-facing roofs, south walls, west walls, east walls, and shading devices will probably be clad with PV.
12. Transparent PV modules can be used as glazing.
13. Energy-efficient appliances and lighting, as well as passive systems, should be used in conjunction with PV.
14. Use PV to generate the necessary high-grade energy of electricity, and use active solar to generate the low-grade thermal energy needed in buildings.
15. Solar swimming-pool heating is the best and most effective way to extend the swimming season in outdoor pools.
16. The area of most solar collectors for pool heating is approximately equal to the pool area in the northern United States and to about half the pool area in the southern United States.
17. Wherever possible, active solar should be used to heat domestic hot water.
18. Active solar space heating should be considered if passive solar heating is not possible.
19. Use radiant floor heating and/or a heat pump in conjunction with the active solar space-heating system.
20. Because solar energy is most available when cooling is required, active solar space cooling has much potential.
21. All south-facing roofs should be covered with a mix of active solar and PV in order to protect the environment, control global warming, and lead society to a sustainable economy.
22. Use transpired collectors on south walls to preheat ventilation air in the winter.
23. Green solar architecture will produce an exciting new aesthetic in harmony with the world.

References

Environmental Building News, July/August 1999, p. 13.

Maycock, P. "1997 World Cell/Module Shipments," *PV News*, February 1998 (updated 2007).

Resources

Further Reading

(See the Bibliography in the back of the book for full citations.)

Kwok, A., and W. Grondzik. *The Green Studio Handbook: Environmental Strategies for Schematic Design*. 2nd ed.

Singh, M. *The Timeless Energy of the Sun for Life and Place with Nature*.

Periodicals

Environmental Building News Solar Today

Solar Today. American Solar Energy Association.

Organizations

(See Appendix K for full citations.)

American Solar Energy Society (ASES) www.ases.org

Florida Solar Energy Center (FSEC) www.fsec.ucf.edu

Interstate Renewable Energy Council (IREC) www.irecusa.org

International Solar Energy Association (ISES), www.ises.org

National Renewable Energy Laboratory (NREL), www.nrel.gov
Good source for detailed information on renewables.

Sandia National Laboratories, www.sandia.gov

Solar Energy Industries Association (SEIA), www.seia.org
SEIA is the national trade organization of PV and thermal manufacturers and component suppliers.

Solar Rating and Certification Corporation, www.solar-rating.org

CHAPTER 9

SHADING AND LIGHT COLORS

Wisdom demands a new orientation of science and technology towards the organic, the gentle, the non-violent, the elegant and beautiful.

E. F. Schumacher,
Small Is Beautiful, ***1973***

The sun control device has to be on the outside of the building, an element of the facade, an element of architecture. And because this device is so important a part of our open architecture, it may develop into as characteristic a form as the Doric column.

Marcel Breuer,
Sun and Shadow

9.1 HISTORY OF SHADING

The prediction by Marcel Breuer on the previous page may yet become a reality because of global warming. Of all the solar strategies, shading may be the most important. The benefits of shading are so great and obvious that we see its application throughout history and across cultures. We see its effect on classical architecture as well as on unrefined vernacular buildings ("architecture without architects").

Many of the larger shading elements had the purpose of shading both the building and an outdoor living space. The porticoes and colonnades of ancient Greek and Roman buildings certainly had this as a major part of their function (Fig. 9.1a). Greek Revival architecture was so successful in the American South because it offered much-needed shading, as well as symbolic and aesthetic benefits. In hot and humid regions, large windows are required to maximize natural ventilation, but at the same time, any sunlight that enters through these large windows increases the discomfort. Large overhangs that are supported by columns can resolve this conflict (Fig. 9.1b). The white color of Greek Revival architecture is also very appropriate for hot climates.

In any good architecture, building elements are usually multifunctional. The fact that the Greek portico also protects against the rain does not negate its importance for solar control. It just makes the concept of a portico all the more valuable in hot and humid regions, where rain is common and the sun is oppressive.

While we need not be as literal as revival architecture, borrowing from the past can be very useful when there are functional as well as aesthetic benefits (Fig. 9.1c). There is a rich supply of historical examples from which to draw. Traditional design features from around the world, while appearing different, often developed in response to the same needs. The Greek portico is closely related to the porch, veranda (from India), balcony, loggia, gallery, arcade, colonnade, and *engawa* (from Japan) (Figs. 9.1a–h).

Chinese, Korean, and Japanese architecture is dominated by the use of large overhangs (Fig. 9.1f). The Japanese traditionally made much use of a veranda-like element called the *engawa*. This large overhang protects the sliding wall panels that can be opened to maximize access to ventilation, light, and view. When the panels are closed, light enters through a continuous translucent strip window above. Also note how rainwater is led down to a drain by means of a hanging chain (Fig. 9.1g). In the early twentieth century, the Greene brothers developed a style appropriate for California by using concepts derived from Japanese architecture (Fig. 9.1h).

Many great architects have understood the importance of shading and used it to create powerful visual statements. Frank Lloyd Wright used shading strategies in most of his buildings. Early in his career, he used large overhangs to both create thermal comfort and make an aesthetic statement about building on the prairie. In his Robie House (Fig. 9.1i), Wright used large areas of operable glazing to maximize natural ventilation during the hot and humid Chicago summers. He understood, however, that this would do more harm than good unless he shaded the glazing from the sun. The very long cantilevered overhangs not only supply the much-needed shade but also create strong horizontal lines that reflect the nature of the region. See Figure 10.8b for a plan view of the Robie House.

Of all architects, Le Corbusier is most closely linked with an aesthetic based on sun shading. It is interesting to note how this came about. In 1932, Le Corbusier designed a multistory building in Paris known as the Cité de Refuge. It was designed

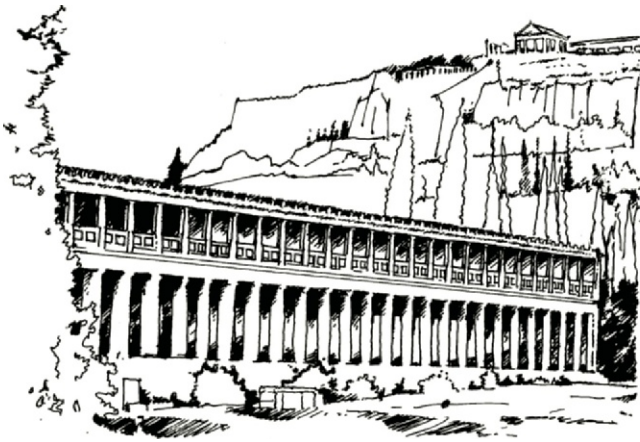


Figure 9.1a Ancient Greek architecture made full use of colonnades and porticoes for protection against the elements and especially the sun. Stoa of Attalos II, Athens.



Figure 9.1b Greek Revival architecture was especially popular in the South, where it contributed greatly to thermal comfort. The Hermitage, Andrew Jackson's home near Nashville, Tennessee.



Figure 9.1c Postmodernism, with its allusion to classical architecture, could draw on time-tested ideas for thermal comfort, as in the public library for San Juan Capistrano, California, designed by Michael Graves.



Figure 9.1d Loggias supported on arcades and colonnades shielded the large windows necessary for natural ventilation in the hot and humid climate of Venice, Italy. Sometimes an open-walled extra floor was added above the top floor to ventilate the heat collecting under the roof.



Figure 9.1e Victorian architecture made much use of the porch and the covered balcony to shade the building and create cool outdoor spaces. Eufaula, Alabama.



Figure 9.1f Much Asian architecture is dominated by large overhangs. Golden Pavilion, Kyoto, Japan. (Courtesy of the Japan National Tourist Organization.)



Figure 9.1g The sliding wall panels can be opened for maximum access to ventilation, light, and view. The engawa, or porch, is clearly visible in this building in the Japanese Garden in Portland, Oregon.

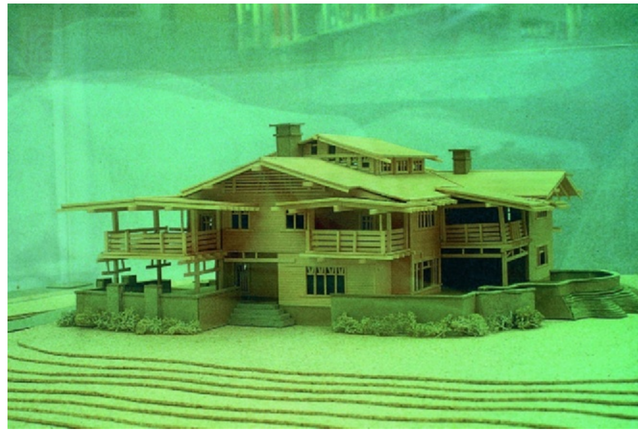


Figure 9.1h The Gamble House in Pasadena, California, 1908, by Greene and Greene, shows the strong influence of Japanese architecture. Note especially the large roof overhangs. Model by Gary Kamemoto and Robert Takei, University of Southern California.



Figure 9.1i Large overhangs dominate the design of the Robie House, Chicago, 1909, by Frank Lloyd Wright.

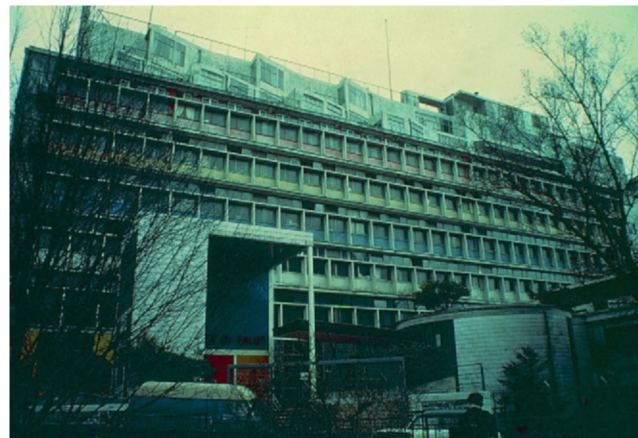


Figure 9.1j Sunshades known as brise-soleil were retrofitted on the Cité de Refuge, Paris, which Le Corbusier designed in 1932 without sunshades. (Photograph by Alan Cook.)

with an all-glass south facade so that a maximum amount of sunlight could warm and cheer the residents. In December passive solar worked wonderfully, but in June the building became unbearably hot. As a result of this mistake, Le Corbusier invented the fixed structural sunshade now known as brise-soleil (sunbreaker). In Figure 9.1j, we see the building after it was retrofitted with a brise-soleil.

Le Corbusier realized the dual nature of the sun—our friend in the winter and our enemy in the summer. His own artwork says it best (see Fig. 6.1). After this realization, shading became a central part of his architecture. For him, the aesthetic opportunities were as important as the protection from the sun. Thus, many of his buildings use sun shading as strong visual element. Some of the best examples come from the Indian city of Chandigarh, where Le Corbusier designed many of the government buildings. The brise-soleil and parasol roof not only shade but also create powerful visual statements in the High Court Building (Fig. 9.1k). The Maharaja's Palace at Mysore has some similarity with the High Court Building, and it is, therefore, tempting to speculate on how much Le Corbusier was influenced by native Indian architecture (Fig. 9.1l). For another example of the parasol roof, see Figure 1.3g, and for another example of the brise-soleil see Figures 10.6ff and 10.6gg.

Traditional buildings often provided shading even when it was not a conscious goal. Because windows were usually set back into deep bearing walls or even thick masonry

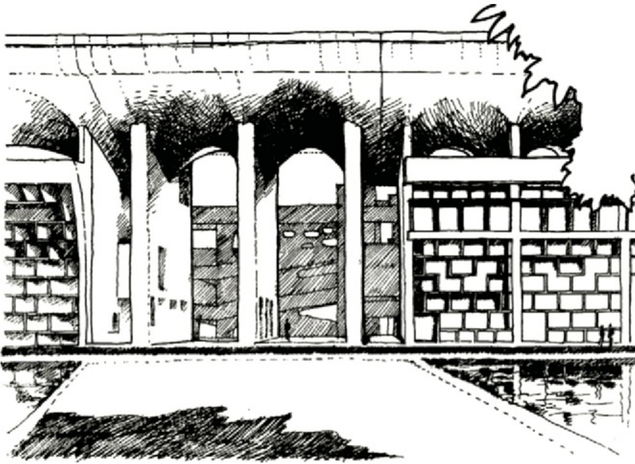


Figure 9.1k The brise-soleil and parasol roof shade the High Court Building at Chandigarh, India. Evaporation from the reflecting pool helps cool the air.



Figure 9.1l The Maharaja's Palace at Mysore, India, illustrates the extensive shading techniques used in some Indian architecture. (Courtesy of the Government of India Tourist Office.)



Figure 9.1m An often-overlooked benefit of the traditional, thick masonry wall was the shading produced from both the vertical and horizontal elements. (Old office building in lower Manhattan.)

curtain walls, the effect was that of a shallow brise-soleil (Fig. 9.1m).

The recent history of the awning gives us insight into how our sense of aesthetics changes. The rendering shown in Figure 9.1n indicates that awnings were considered a desirable aesthetic object in the first half of the twentieth century. When air-conditioning became available, richer people could afford to abandon the use of awnings, while the poor still used them. Consequently, awnings were associated with poor and rundown buildings. Fortunately, the functional and aesthetic benefits of awnings are being rediscovered in the twenty-first century.



Figure 9.1n As this architect's rendering indicates, awnings were considered desirable in the early twentieth century for both their functional and their aesthetic benefits. (From *Golf and Country Clubs* by Clifford C. Wendehack.)

9.2 SHADING

Passive solar heating works! It works even better in the summer, because there is much more sun and the outdoor temperature is much higher. Thus, shading is required to prevent passive solar heating in the summer.

Shading is one of the most important sustainability strategies because almost all buildings in the world overheat in the summer and the usual response is to get energy-guzzling air conditioners. Consequently, the energy needed for air-conditioning will increase exponentially as more people, especially in the developing world, can afford it (see Fig. 1.10c). This huge increase in energy demand for cooling must be minimized by heat avoidance and passive cooling, and the number-one heat-avoidance strategy is shading, which is part of tier one of the three-tier design approach to cooling a building (Fig. 9.2a). The second tier consists of passive cooling, and the third uses mechanical equipment to cool whatever the architectural strategies of tiers one and two could not accomplish.

Although shading of the whole building is beneficial, shading of the windows is crucial, so most of the following discussion focuses on the shading of windows.

Shading is a solar strategy even though it blocks rather than collects solar radiation—it creates "negawatts" instead of megawatts. To be effective, shading requires a better understanding of solar geometry than any of the other solar strategies of passive solar, active solar, PV, and daylighting.

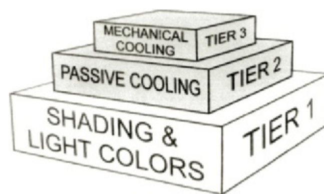


Figure 9.2a The three-tier approach to design is a logical and sustainable method for achieving thermal comfort in the summer. Heat avoidance and shading are part of tier one.

Which window orientations need the most shading in the summer? The graph in Figure 9.2b shows that on June 21, a skylight (horizontal glazing) collects about four times more solar radiation than a south window. Clearly, then, skylights need very effective shading or, better yet, should be avoided. Figure 9.2b also shows that east or west glazing collects more than two times the solar radiation of south windows. Thus, the shading of east and west windows is also more important than the shading of south windows.

If the graph in Figure 9.2b looks familiar, it is not surprising, since

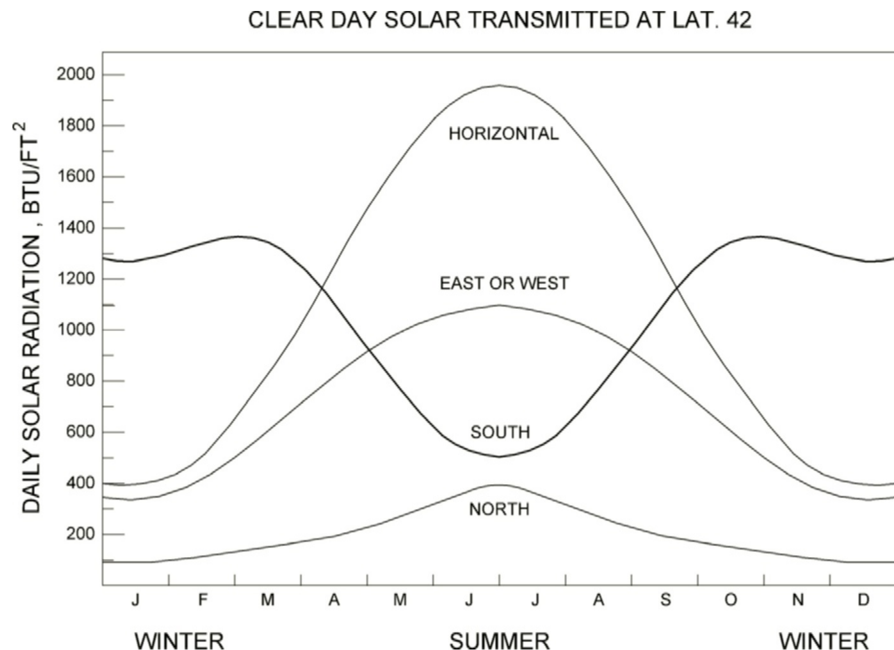


Figure 9.2b All orientations except south receive maximum solar radiation in summer. A skylight receives about four times the solar heating that south windows receive on June 21. (After the *Workbook for Workshop on Advanced Passive Solar Design*, by J. Douglas Balcomb and Robert Jones, © J. Douglas Balcomb, 1987.)



Figure 9.2c In the Conoco Headquarters complex in Houston, Texas, Kevin Roche was inspired by the local Texas plantation style with its large overhangs and column-supported porches. The awning-like translucent overhangs are 13 ft (4 m) deep because they shade two floors, face in all directions of the compass, protect verandas, and block the sky and its strong, diffuse radiation in a humid climate. Trellises covered with jasmine and fig ivy protect the first floor, as well as the courtyards where the second-story verandas leave off. In this very hot and wet climate, even the on-grade parking is protected by awning-like fiberglass sunshades (not shown).

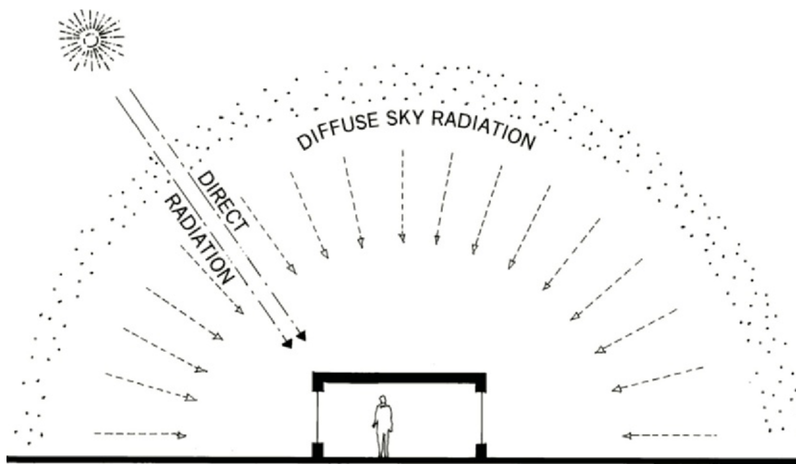


Figure 9.2d In humid, polluted, and dusty regions, the diffuse-sky component is a large part of the total solar load.

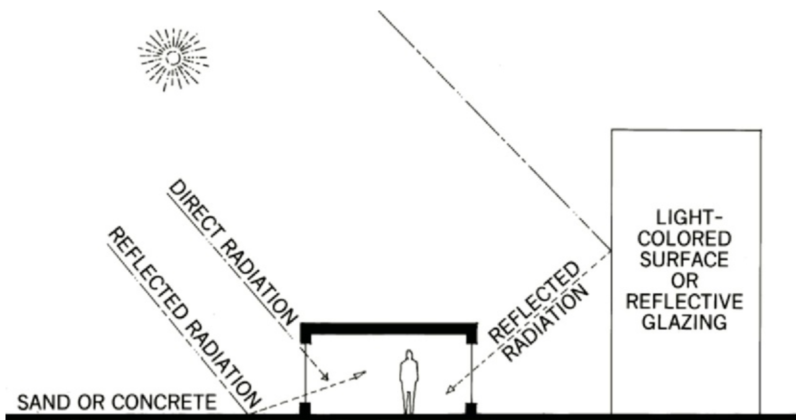


Figure 9.2e In dry regions, the solar load consists mainly of the direct and reflected components. However, reflective glazing can be a problem in all climates.

a variation of it appeared as Figure 7.16a, which was used to show how much more solar radiation south windows collect than any other orientation in the winter. Thus, south windows are very desirable from both a shading and a passive solar heating point of view. Skylights should be avoided because they collect a large amount of solar radiation in the summer and little in the winter. Similarly, east and west windows are not desirable from both heating and cooling points of view.

The total solar load consists of three components: direct, diffuse, and reflected radiation. To prevent passive solar heating when it is not wanted, one must always shade a window from the direct solar component and often also from the diffuse sky and reflected components. In sunny humid regions like the Southeast, the diffuse sky radiation can be very significant (Fig. 9.2c). Sunny areas with much dust or pollution can also create much diffuse radiation (Fig. 9.2d). Reflected radiation, on the other hand, is often a large problem in such areas as the Southwest, where intense sunlight and high-reflectance surfaces often coexist. The problem also occurs in urban areas, where highly reflective surfaces are quite common. There are cases where the north facade of a building experiences the solar load of a south orientation because a large building with reflective glazing was built toward the north (Figs. 9.2e and 9.2f).

The type, size, and location of a shading device will, therefore, depend in part on the size of the direct, diffuse, and reflected components of the total solar load. The reflected component is usually best controlled by reducing the reflectivity of the offending surfaces, and this is often accomplished by the use of plants. The diffuse-sky component is, however, a much harder problem because radiation comes from a large exposure angle. It is, therefore, usually controlled by extralarge shading devices, additional indoor shading devices, or shading within the glazing. The direct solar component is effectively controlled by exterior shading devices.

The need for shading might seem to conflict with the demand for daylighting. Fortunately, when solar energy is brought into a building in a very controlled manner, it can supply high-quality lighting with less heat gain than what would be produced by the electric lighting. This is accomplished by allowing just enough light to enter so that the electric lights can be turned off. A more detailed discussion of daylighting versus shading is found in Section 13.6.

When it is not used for daylighting, solar radiation should be blocked during the overheated period of the year. A residence in the North would experience an overheated period that is only a few months long. That same residence in the South or a large office building in the North could experience overheated periods that are two to three times as long. Thus, the required shading period for any building depends on both the climate and the nature of the building. Shading periods are discussed in Section 9.5 below.

Shading can be accomplished by exterior devices, by glazing, or by indoor shading devices. Although indoor shading is almost always movable, exterior shading can and often should be movable. Figure 9.2g shows that exterior shading devices are best at shading direct sunlight.



Figure 9.2f Glass facades without exterior shading devices reflect much of the sun. The bright spots on the north side of this building are a result of reflections from the building on the left.

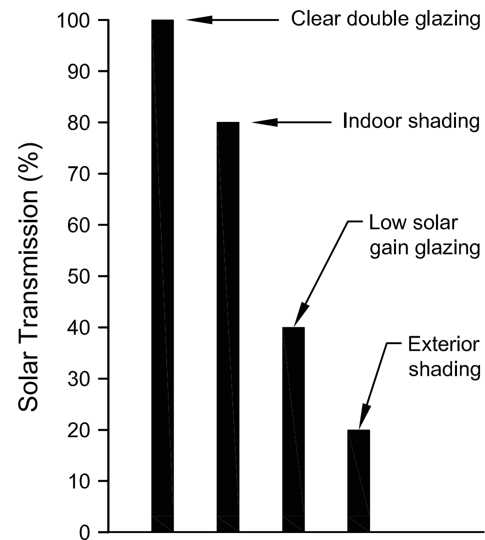


Figure 9.2g Exterior shading devices block about 80 percent of the solar gain through clear windows, while indoor shading blocks only about 20 percent. Low solar gain glazing blocks almost as much solar gain as exterior shading, but, unfortunately, also blocks much of the winter sun and light from the view.

The goal of a shading design is not just to keep the sun out but also to allow as much view as possible. After all, most people agree that the most important function of a window is to provide a view. The shading design guidelines presented here help the designer preserve the view as much as possible.

External shading devices are discussed first and in most detail because they are the most effective barrier against the sun and have the most pronounced effect on the aesthetics of a building.

9.3 FIXED EXTERIOR SHADING DEVICES

As with passive solar systems, orientation is also critical with shading. Each orientation requires a different shading strategy. The horizontal overhang on south-facing windows is very effective during the summer because the sun is then high in the sky. Although less effective, the horizontal overhang is also the best on the east, southeast, southwest, and west orientations. In very hot climates, north windows also need to be shaded because during the summer the sun rises north of east and sets north of west. Since the sun is low in the sky at these times, the horizontal overhang is not effective, and small vertical fins work best on the north facade (Fig. 9.3a).

East- and west-facing windows pose a difficult problem because of the low-altitude angle of the sun in the morning and afternoon. The best solution by far is to avoid using east and especially west windows as much as possible. The next best solution is to have the windows on the east and west facades face north or south, as shown in the plans in Figure 9.3b and the photos in Figures 9.3c, d, and e. If that is also not possible, then minimize the window height and use horizontal overhangs. However, it must be understood that if the shading

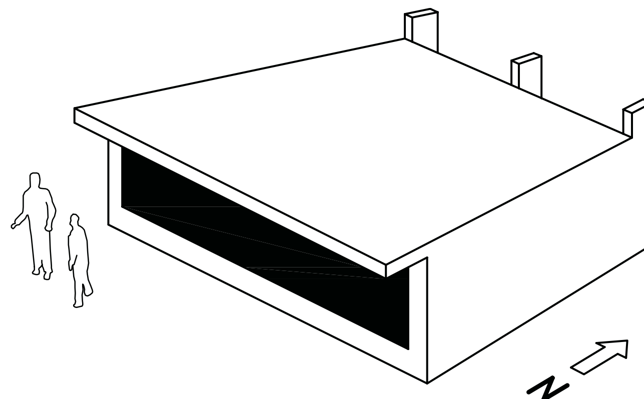


Figure 9.3a Each orientation requires a different shading strategy. From a shading point of view, east and west windows are best avoided, because they cannot be shaded well.

(a) (b) (c)

N

Sight lines

(d) (e)

Figure 9.3b These plans illustrate how windows on east and west facades can face either north or south.

devices on the east and west are to be very effective, they will severely restrict the view.

In some cases, a combination of vertical and horizontal elements can be used, as shown in Figure 9.3f. When these elements are closely spaced, the system is called an **eggcrate**.

Since the problem of shading is one of blocking the sun at certain angles, many small devices can have the same effect as a few large ones, as shown in Figure 9.3g. In each case, the ratio of length of overhang to the vertical portion of the window shaded



Figure 9.3c All the windows on this west facade face north and south. This building is the library of the University of Arkansas at Fayetteville.



Figure 9.3d The windows on the west facade of this building in Fez, Morocco all face north.

is the same. Screens are available that consist of miniature louvers (about ten per inch) that are very effective in blocking the sun and yet are almost as transparent as insect screens.

Because view is the highest priority for most windows, a single large horizontal overhang is usually the best choice. Although it obstructs the high sky, the more important horizontal view is unimpeded.

Skylights (horizontal glazing systems) create a difficult shading problem because they face the sun most directly during the worst part of the year—summer at noon (Fig. 9.3h). Therefore skylights, like east and west windows, should be avoided. A much better solution for letting year-round daylight and winter sun enter through the roof is the use of clerestory windows (Fig. 9.3i; see also Figs. 7.6e and 7.6f). The vertical glazing in the clerestory can then be shaded by the window techniques explained in this chapter. If domed-type skylights are to be used, consider using exterior shading devices to block the high summer sun.

Table 9.3 shows some of the most common fixed exterior shading devices. They are all variations of either the horizontal overhang, the vertical fin, or the eggcrate, which is a combination of



Figure 9.3e The windows on the west facade of this building at Georgia Tech all face north.

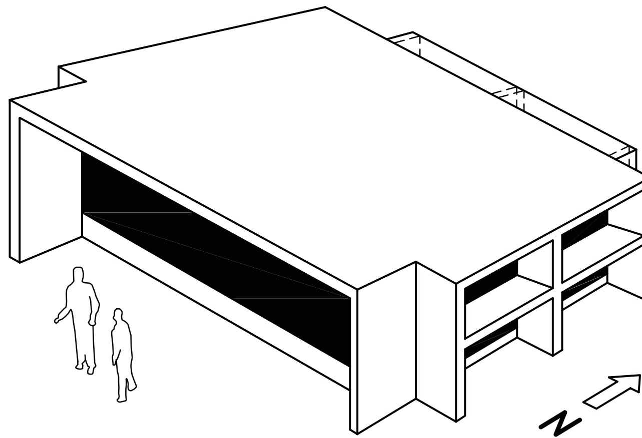


Figure 9.3f Shading is improved when a combination of vertical and horizontal elements is used.

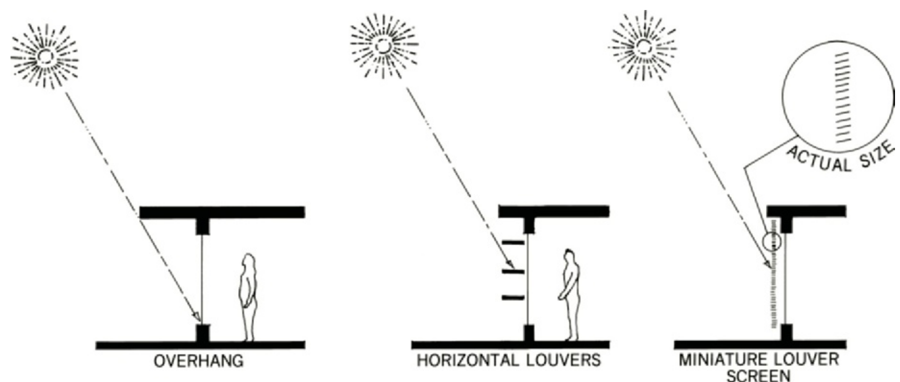


Figure 9.3g Many small elements can create the same shading effect as one large device. However, the view is best with the large overhang.

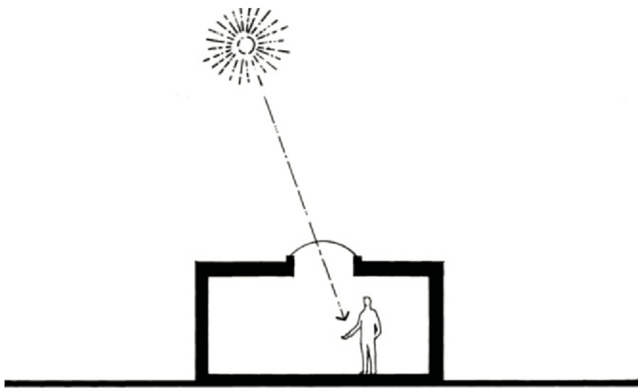


Figure 9.3h Skylights (horizontal glazing) should usually be avoided because they collect the most sunlight in the summer and the least in the winter.

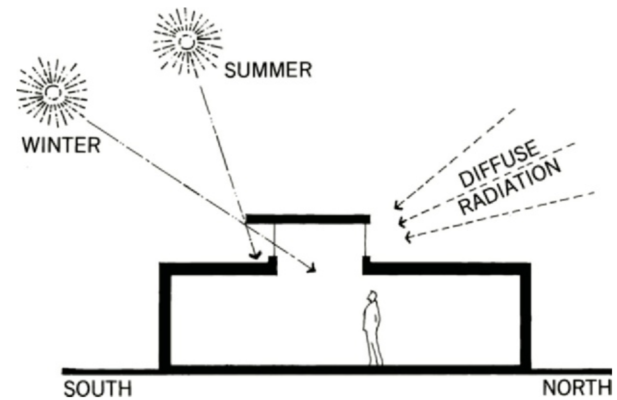


Figure 9.3i Clerestory windows should be used instead of skylights because they allow the sun to enter in a controlled manner, and south-facing clerestories collect more sun in the winter than the summer.

Table 9.3 Examples of Fixed Shading Devices

		Descriptive Name	Best Orientation*	Comments
I		Overhang Horizontal panel or awning	South, east, west	Traps hot air Can be loaded by snow and wind Can be slanted
II		Overhang Horizontal louvers in horizontal plane	South, east, west	Free air movement Snow or wind load is small Small scale Best buy!
III		Overhang Horizontal louvers in vertical plane	South, east, west	Reduces length of overhang View restricted Also available with miniature louvers
IV		Overhang Vertical panel	South, east, west	Free air movement No snow load View restricted
V		Vertical fin	North	Restricts view if used on east and west orientations
VI		Vertical fin slanted	East, west	Slant toward north in hot climates and south in cold climates Restricts view significantly **Not recommended**
VII		Eggcrate	East, west	For very hot climates View very restricted Traps hot air **Not recommended**

**For temperate climates. In the tropics, north becomes similar to south, and at the equator they are equal.*
Source: Architectural Graphic Standards, 8th ed. John R. Hoke, ed. (Wiley, 1988).

the first two. The louvers and fins can be angled for additional solar control. Almost an infinite number of variations are possible, as can be seen by looking at the work of such architects as Le Corbusier, Oscar Niemeyer, Richard Neutra, Paul Rudolph, and E. D. Stone. For examples of the work of these and many other architects, the author highly recommends the book *Solar Control and Shading Devices*, by Olgyay and Olgyay.

Fixed rather than movable shading devices are often used because of their simplicity, low cost, and low maintenance. Their effectiveness is limited, however, for several signification reasons, and movable shading devices should be seriously considered.

9.4 MOVABLE SHADING DEVICES

It is not surprising that movable shading devices respond better to the dynamic nature of the environment than do static devices. Since full shade is needed during the overheated periods and full sun during the underheated periods, a shading device must be in phase with the thermal conditions. With a fixed shading device, the period of solar exposure to the window is not a function of temperature but rather of sun position.

The main reason for the discrepancy between sun angles and temperature is that the solar year and the thermal year are out of phase. Because of its great mass, the earth heats up slowly in spring and does not reach

its maximum summer temperature until one or two months after the day of maximum heating, the summer solstice (June 21). Similarly in the winter, there is a one- to two-month time lag in the cooling of the earth. The minimum heating effect from the sun comes on December 21, while the coldest days are in January or February.

Fixed overhangs perform poorly because they respond to the solar year rather than the thermal year (Colorplate 38). This is illustrated by the four sections shown in Figure 9.4a in which the overhang was designed for a climate where it is hot through September 21 and cold through March 21. Therefore, for high performance the sun should be shaded until September 21 and not shaded until March 21. Since the sun angle is the same on these two days, the overhang cannot simultaneously both fully shade and fully not shade at the same time (see IV in Fig. 9.4a).

Section I in Figure 9.4a shows the sun when it is lowest in the sky (December 21). Note that part of the window is always in shade. Section II shows that even more of the window is in shade on January 21 when it is even colder. Section III shows that most of the window is in shade on

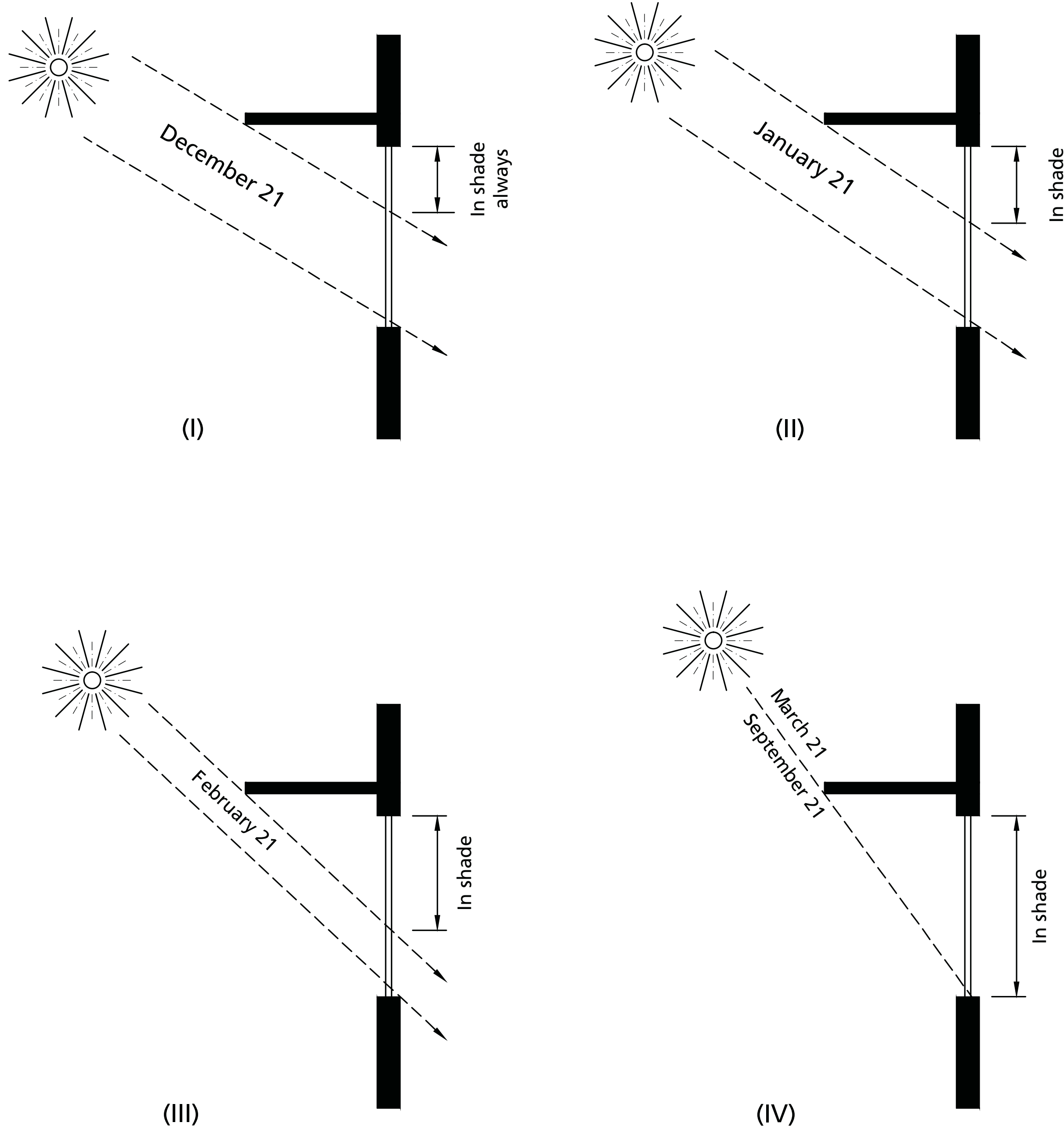


Figure 9.4a The importance of movable south overhangs is demonstrated by the poor performance of a fixed overhang. The overhang shown here was designed for a realistic location where shading is needed through September 21 and where it is cold through March 21 (see section IV). Note how much of the window is in shade during the coldest months of January and February, preventing effective passive solar heating of the building.

February 21 when it is still very cold. Finally, on March 21 when this climate still requires heating, the window is in complete shade (IV). Clearly, a fixed overhang that shades fully in the summer will prevent effective passive solar heating in the winter.

The same window is shown in plan view in Figure 9.4b. The largest puddle of sunlight occurs on December 21, when the sun is lowest and least shaded by the overhang. The desirable puddle of sunlight is smaller on January 21 and even smaller on February 21, when it is very cold and a maximum of sunlight should be collected. And on March 21, when solar heating is still desired, no sun enters the window. For additional emphasis, this same phenomenon is shown in elevation in Figure 9.4c.

Thus, any overhang that fully shades the summer sun will also shade too much in the winter. By making the overhang shorter, there will more winter sun but also more overheating in the summer with year-round performance no better. Unfortunately, fixed overhangs on south windows provide mediocre performance, which is unacceptable at a time when buildings must be designed for high performance. Fortunately, movable overhangs can provide full sun when it is cold and full shade when it is hot.

Although this example was for one particular latitude and climate, the same problem with fixed overhangs

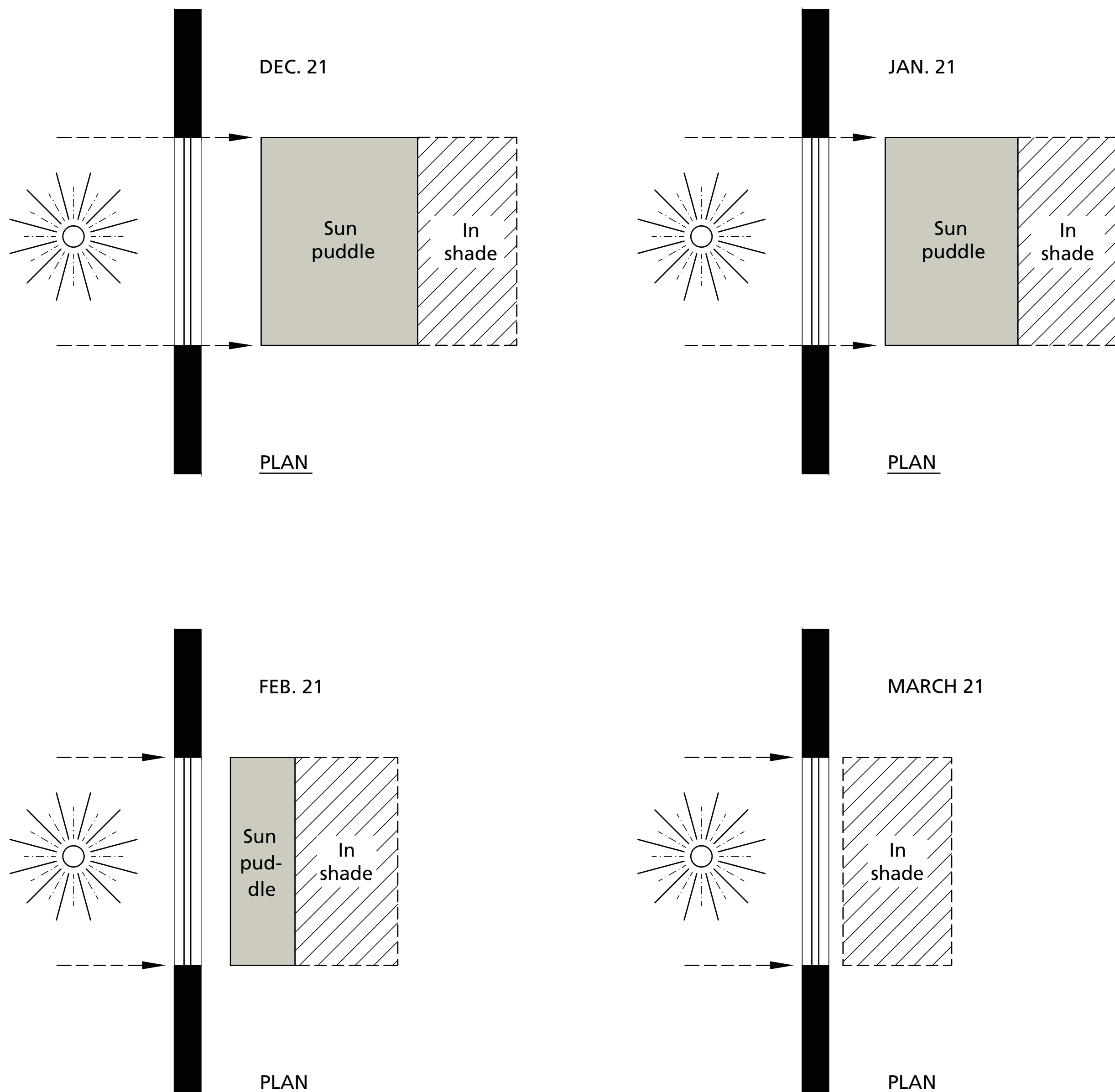


Figure 9.4b Because of the myth that fixed overhangs can both effectively shade in the summer and allow solar collection in the winter, the poor performance of a fixed overhang shown in section in Figure 9.4a is shown here in plan. Note the size of the sun puddles compared to what they would have been without shading.

occurs whenever winter sun and summer shade are both needed. Fixed overhangs are appropriate only for climates and building types where solar heating is not required.

The movement of shading devices can be very simple or very complex. An adjustment twice a year can be quite effective, yet simple. Late in spring, at the beginning of the overheated period, the shading device is manually extended. After the last day of the overheated period in late fall, the device is retracted for full solar exposure (Fig. 9.4d).

Before air-conditioning became available, awnings were used to effectively shade windows in the summer. Awnings were used on many buildings but were particularly common on luxury buildings, such as major hotels (Fig. 9.4e). In the winter, the awnings were removed to let more sun and light enter the building. Modern awnings are excellent shading devices. They can be durable, attractive, and easily adjustable to meet requirements on a daily and even hourly basis (Fig. 9.4f and Colorplate 28). Movable shading devices that adjust to the sun on a daily basis are often automated, while those that need to be adjusted only twice a year are usually manually operated. Table 9.4 presents a variety of movable shading devices.

In many ways, the best shading devices are deciduous plants, most of which are in phase with the thermal year because they gain and lose their leaves in response to temperature changes. Other advantages of deciduous plants include low-cost, aesthetically pleasing quality, ability to reduce glare, visual privacy, and ability to cool the air by transpiration from the leaves.

The main disadvantage of using plants is the fact that leafless plants still create some shade, with some types much more than others (Fig. 9.4g). Thus, trees are not recommended in front of south windows. Furthermore, it is no longer desirable to shade the roof, which should now

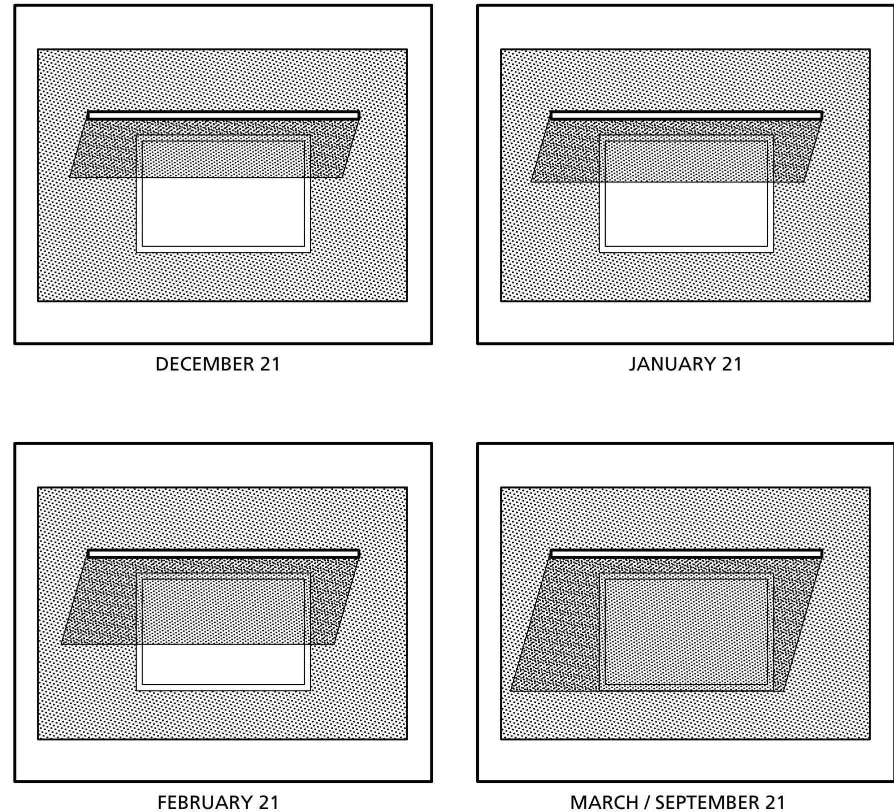


Figure 9.4c The poor performance of a fixed overhang as shown in Figure 9.4a is shown here in elevation for further emphasis. After all, it is hard for a much believed and promoted myth to be busted.

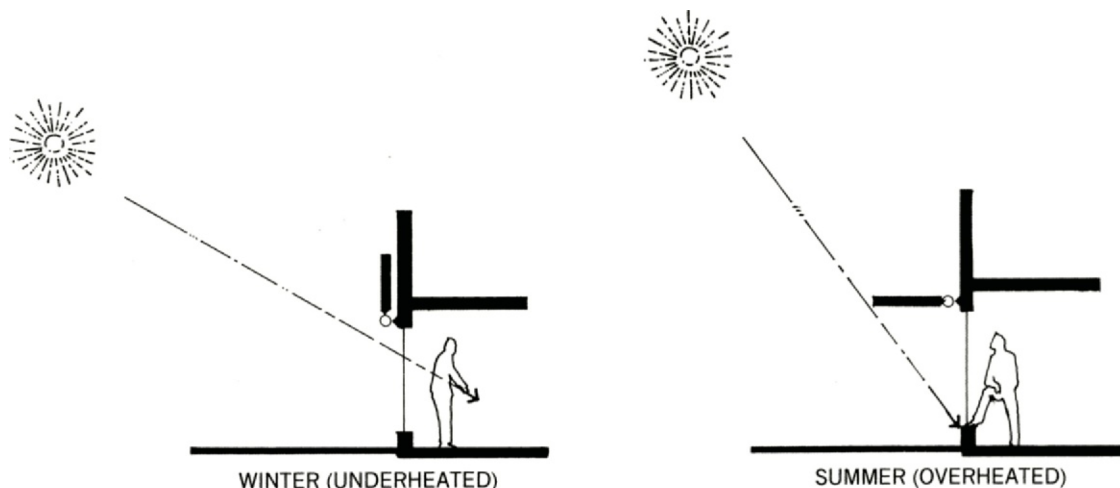


Figure 9.4d A movable shading device with just two simple adjustments per year can function extremely well.



Figure 9.4e Awnings were a common element on many buildings until air conditioning became common. After giving effective shade in the summer, they were removed in order to allow more sun and light to enter the building in the winter.

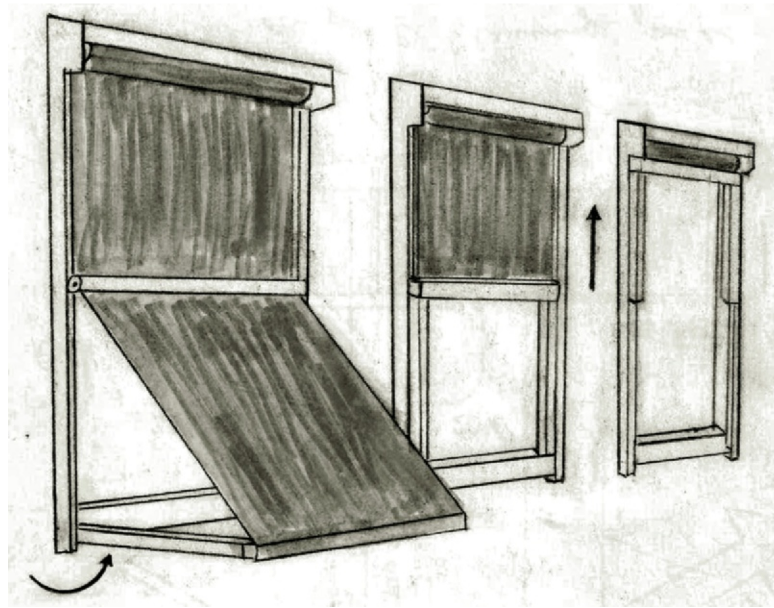


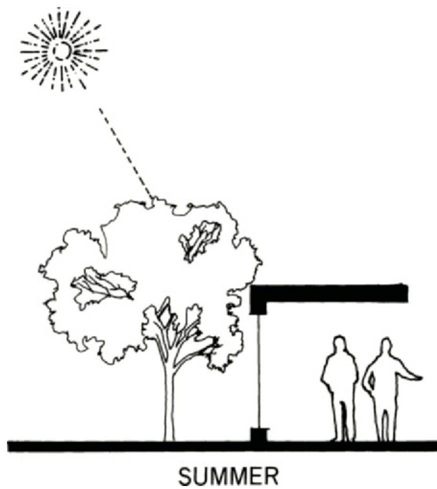
Figure 9.4f Roll-down exterior fabric shades are very popular in Europe. By folding out the lower section, they provide ventilation and a limited view.

Table 9.4 Examples of Movable Shading Devices

	Descriptive Name	Best Orientation	Comments
IX	Overhang Awning	South, east, west	Fully adjustable for annual, daily, or hourly conditions Traps hot air Good for view Can be retracted during storms Best buy!
X	Overhang Rotating horizontal louvers	South, east, west	Will block some view and winter sun
XI	Fin Rotating fins	East, west	Much more effective than fixed fins Less restricted view than slanted fixed fins
XII	Deciduous plants Trees Vines	East, west southeast, southwest northeast northwest	View restricted but attractive for low-canopy trees Self-cooling **Highly recommended**
XIII	Exterior roller shade	East, west, southeast, southwest northeast northwest	Very flexible, from completely open to completely closed View is restricted when shade is used **Provides security**

collect sun for active solar hot-water heaters and PV arrays for generating electricity. Other disadvantages include slow growth, limited height, and the possibility of disease destroying the plant. However, vines growing on a trellis or hanging from a planter can overcome many of these problems (Figs. 9.4h and 9.4i). Given enough time, vines will grow to great heights. In hot climates, there is great benefit in shading not only windows but also walls. The darker the wall, the greater the benefit (Fig. 9.4j). A study in Miami of a moderately sparse vine 3 in. (7 cm) thick on a west wall resulted in a drop of the wall temperature by 8°F (4.5°C) in the morning and 14°F (8°C) in the afternoon. For examples of vines and trees for shading see Section 11.9. In general, the east and west orientations are the best locations for deciduous plants.

Another very effective movable shading device is the exterior roller shade. The Bateson office building makes very effective use of exterior fabric roller shades (Fig. 9.4k). A roller shade made of rigid slats is very popular in Europe and is now available here (Fig. 9.4l). It offers security as well as very effective shading. These shading devices are especially



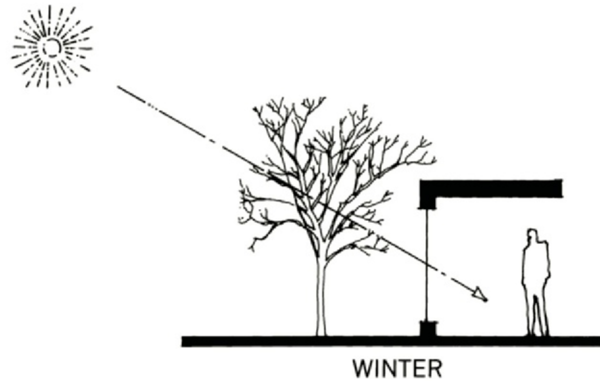
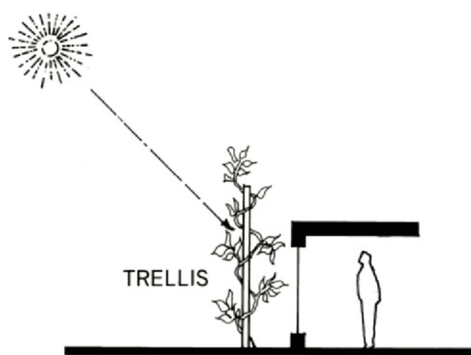


Figure 9.4g The shading from trees depends on the species, pruning, and maturity of the plants. Transmission can be as low as 20 percent in the summer and as high as 70 percent in the winter. Unfortunately, with some trees, winter transmission can be as low as 40 percent.



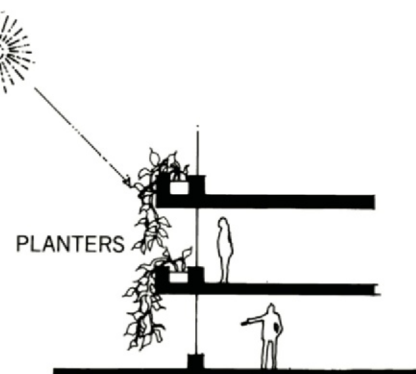


Figure 9.4h Vines can be very effective sunshading devices. Some vines grow as much as 30 ft (9 m) in one year. (See also Colorplate 30.)



Figure 9.4i Since trees grow too slowly to help much on multistory buildings, planters can bring shade plants to each level almost immediately. (See also Colorplates 30 and 34.)

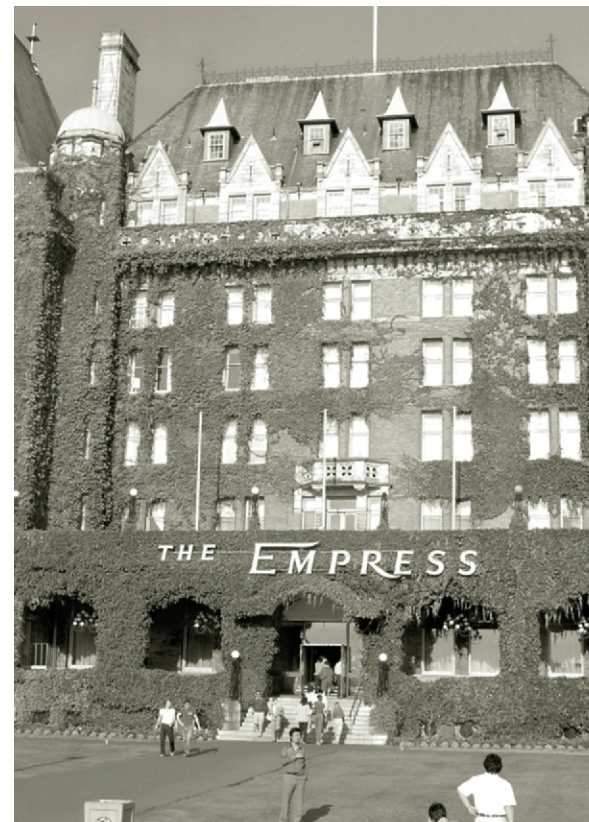


Figure 9.4j Medium- to dark-colored walls in hot climates benefit greatly from a vine cover. (See also Colorplate 27.)



Figure 9.4k The automated fabric roller shades on the exterior of east and west windows are guided by vertical support cables which keeps the shades from swaying in the wind.

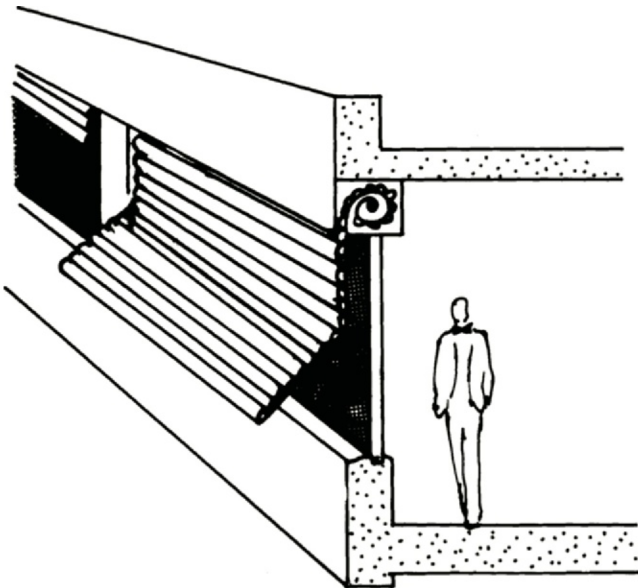


Figure 9.4l Exterior roller shades made of rigid slats move in a vertical plane, and some can also project out like an awning.

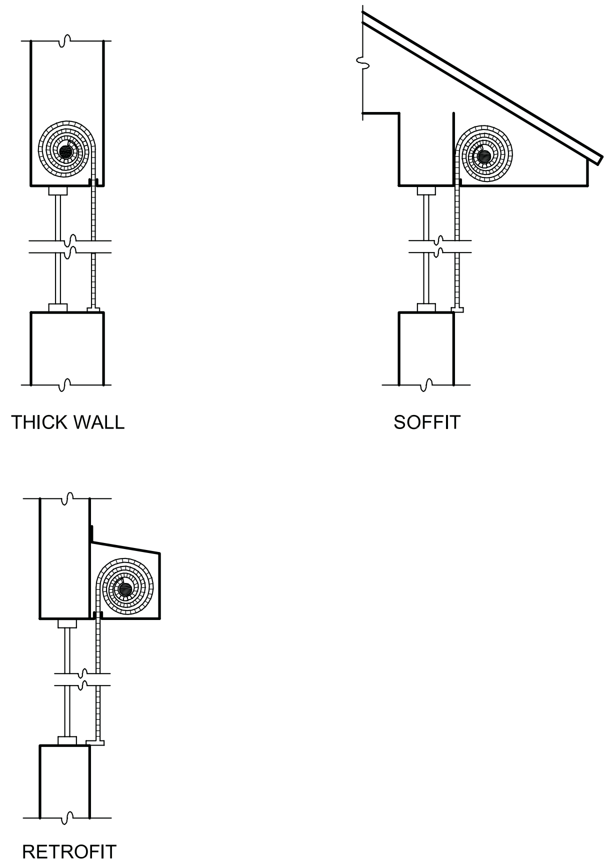


Figure 9.4m Although it is best to integrate exterior roller shades into the design of a new building, they can be added to existing buildings.

appropriate on difficult east and west exposures, where for half a day no shading is necessary and for the other half almost full cover is required. Figure 9.4m shows how these roller shades are mounted on or in a building.

It has been said that the great inventions of humankind are fire, the wheel, and the venetian blind. The venetian blind just got better—it can now be used outdoors as well as indoors, and the outdoor venetian blinds allow the same great range of adjustments as the indoor kind. Of course, the outdoor venetian blind is much more effective



Figure 9.4n Exterior venetian blinds have all of the adjustments possible with interior venetian blinds, but they are much more effective in keeping the sun out. They also make an architectural statement on the facade. This building is in Freiburg, Germany.

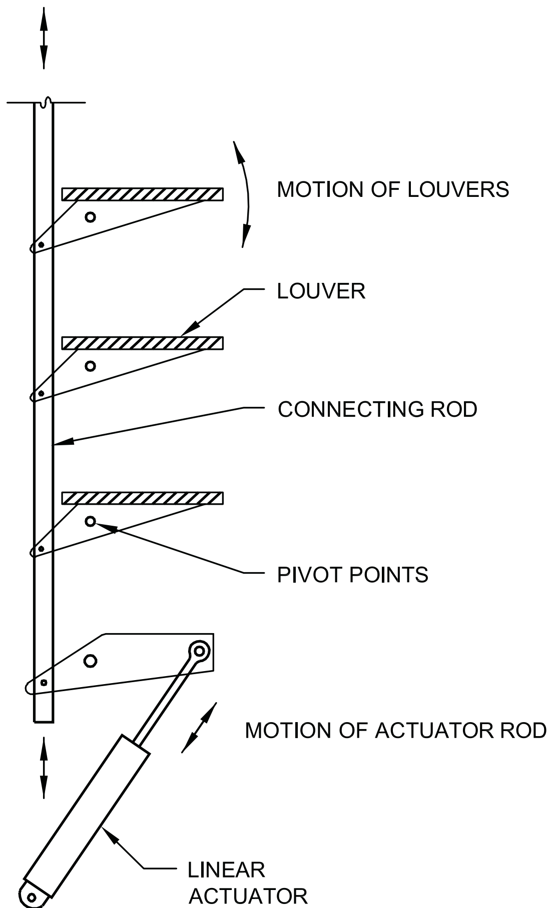


Figure 9.4o Adjustable exterior louvers are effective sun-control devices, but they will always obstruct the view somewhat, unlike exterior venetian blinds, which can be drawn up out of the way. Actuators are often used to rotate a whole column or row of movable louvers.



Figure 9.4p This employment of adjustable louvers is in the Chiswick Business Park in London, UK. (Courtesy of Enjoy-Work).

in keeping the sun out, and it has the same good daylighting control as the indoor type. The outdoor type is widely used on commercial buildings in Germany (Fig. 9.4n).

A similar but less flexible system is to have exterior louvers that only rotate. The partial obstruction of the view is a major disadvantage of these outdoor louvers or fins. Figure 9.4o shows how one actuator can operate a whole panel of louvers. Figure 9.4p shows an employment of exterior louvers in a London office building.

There is a widely held conviction that since a building should be as low maintenance as possible, movable shading devices are unacceptable. This is a little like saying that because an automobile should be low maintenance, the wheels should be fixed and not allowed to turn. The author believes that the use of existing technology and careful detailing can produce trouble-free, low-maintenance, movable shading devices. Furthermore, the mediocre performance of fixed shading devices is no longer acceptable in any climate that requires winter heating.

9.5 SHADING PERIODS OF THE YEAR

Windows need shading during the overheated period of the year, which is a function of both climate and building type. From a heating and cooling point of view, buildings can be divided into two main types: envelope dominated and internally dominated.

The envelope-dominated building is very much affected by the climate because it has a large surface-area-to-volume ratio and because it has only modest internal heat sources. The internally dominated building, on the other hand, tends to have a small surface-area-to-volume ratio and large internal heat gains from such sources as machines, lights, and people. See Table 9.5A for a comparison of the two types of buildings.

A more precise way to define buildings than by the above two types is the concept of balance point temperature (BPT). Buildings do not need heating when the outdoor temperature is only slightly below the comfort zone because there are internal heat sources (lights, people, machines, etc.) and because the skin of the building slows the loss of heat. Thus, the greater the internal heat sources and the more effectively the building skin can retain heat, the lower will be the outdoor temperature before heating will be required. The BPT is the outdoor temperature below which heating is required. It is a consequence of building design and function, not climate. The BPT for a typical internally dominated building is about 50°F (10°C), and for a typical envelope-dominated building it is about 60°F (15°C).

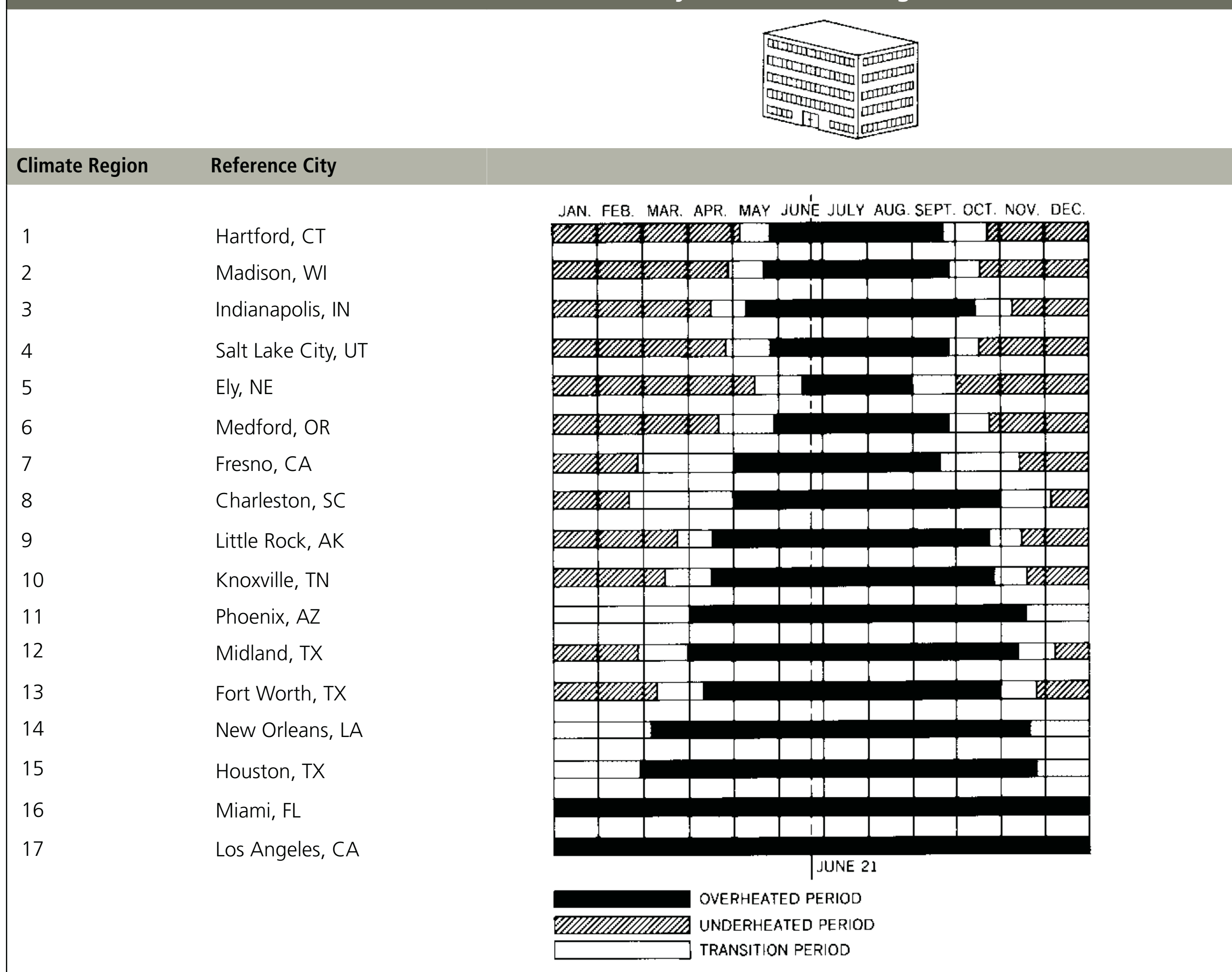
Since the comfort zone has a range of about 10°F (5°C), roughly

Table 9.5A Comparison of Envelope-Dominated and Internally Dominated Building Types

Characteristic	Envelope Dominated	Internally Dominated
Balance point temperature	60°F (15°C)*	50°F (10°C)
Building form	Spread out	Compact
Surface-area-to-volume ratio	High	Low
Internal heat gain	Low	High
Internal rooms	Very few	Many
Number of exterior walls of typical room	1 to 3	0 to 1
Use of passive solar heating	Yes, except in climates with no winters	No, except in very cold climates
Typical examples	Residences, small office buildings, small schools	Large office and school buildings, auditoriums, theaters, factories

*Superinsulated buildings tend to have a balance point temperature of about 50°F (10°C) even though the other characteristics are those of an envelope-dominated building.

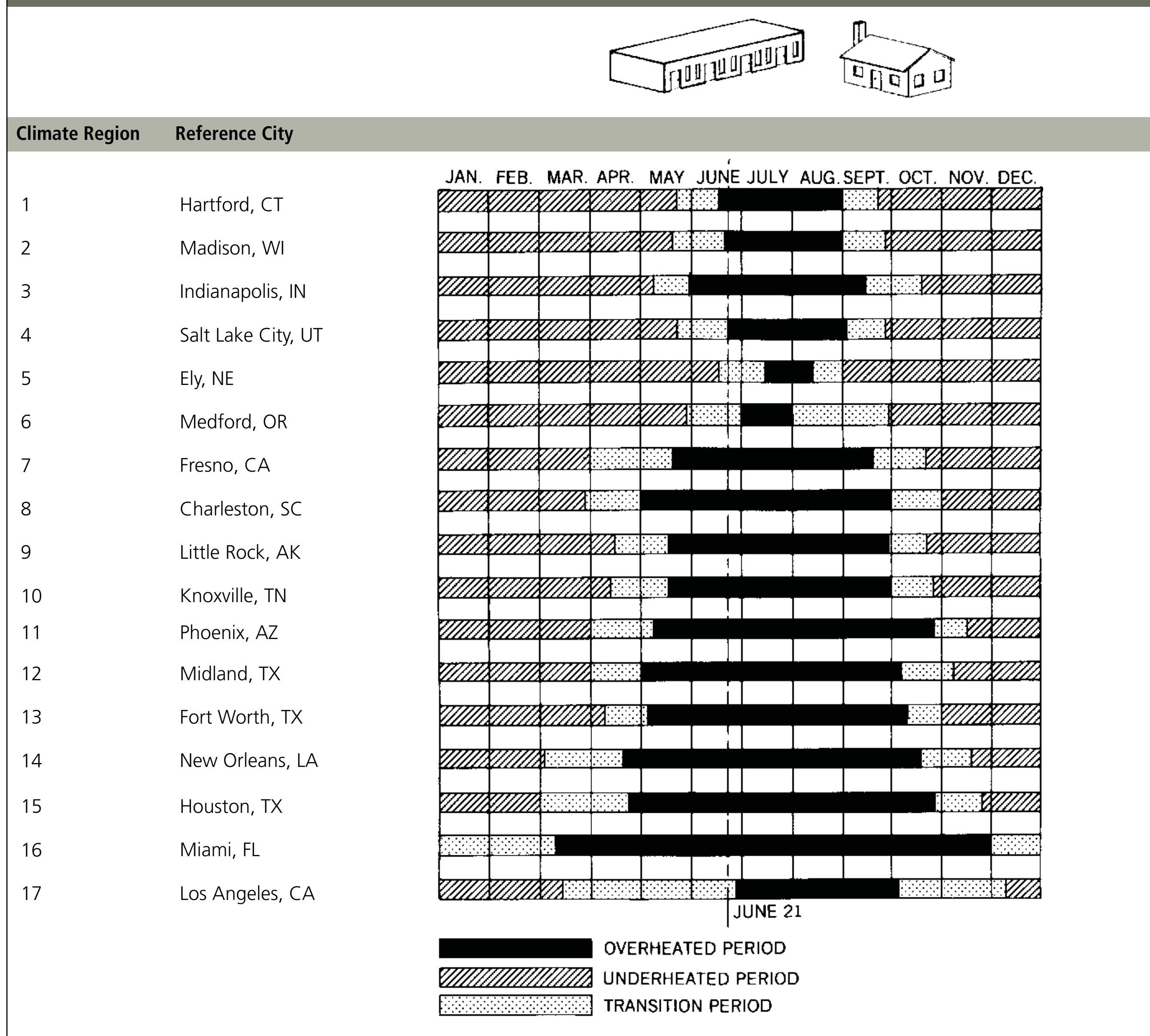
Table 9.5B Overheated and Underheated Periods for Internally Dominated Buildings



Climate Region	Reference City
1	Hartford, CT
2	Madison, WI
3	Indianapolis, IN
4	Salt Lake City, UT
5	Ely, NE
6	Medford, OR
7	Fresno, CA
8	Charleston, SC
9	Little Rock, AK
10	Knoxville, TN
11	Phoenix, AZ
12	Midland, TX
13	Fort Worth, TX
14	New Orleans, LA
15	Houston, TX
16	Miami, FL
17	Los Angeles, CA

Notes:
This table is for well-constructed, modern, internally dominated buildings (BPT = 50°F [10°C]).
The overheated period occurs when average daily outdoor temperature is greater than 60°F (15°C).
The underheated period occurs when average daily outdoor temperature is under 50°F (10°C).
The climates shown are for the given reference cities. The climates at the boundaries are the average of the adjacent regions.

Table 9.5C Overheated and Underheated Periods for Envelope-Dominated Buildings



Notes:
This table is for well-constructed, modern, envelope-dominated buildings (BPT = 60°F [15°C]).
The overheated period occurs when average daily outdoor temperature is greater than 70°F (21°C).
The underheated period occurs when average daily outdoor temperature is under 60°F (15°C).
The climates shown are for the given reference cities. The climates at the boundaries are the average of the adjacent regions.

68° to 78°F (20° to 25°C), the overheated period of the year starts at about 10°F (5°C) above the BPT of any building. For example, for an internally dominated building (BPT = 50°F [10°C]) the overheated period would start when the average daily outdoor temperature reached about 60°F (15°C). Consequently, the lower the BPT of a particular building, the shorter will be the underheated period (heating season), and the longer will be its overheated period (cooling season) during which time shading is required.

Table 9.5B shows the over- and underheated periods of the year for internally dominated buildings (BPT = 50°F [10°C]) in each of the seventeen climate regions, while Table 9.5C gives the same information for envelope-dominated buildings (BPT = 60°F [15°C]). Note how much shorter the overheated periods are in Table 9.5C compared to Table 9.5B. Also, it is very important to note that the overheated periods are never symmetrical about June 21. As mentioned earlier, the thermal year is always out of phase with the solar year.

Keep in mind that the climates described are for the reference city in each climate region. Near boundaries between two regions it may be necessary to interpolate the two climates.

9.6 OVERHANGS

Most shading devices consist of either overhangs, vertical fins, or a combination of the two. The overhang and its many variations are the best choice for the south facade. Because they are directionally selective in a desirable way, they can block the sun but not the view. Overhangs can also be designed to block the high summer sun while allowing the lower winter sun to enter the window. Although slightly less effective, overhangs are also the best choice for southeast, southwest, east, and west windows.

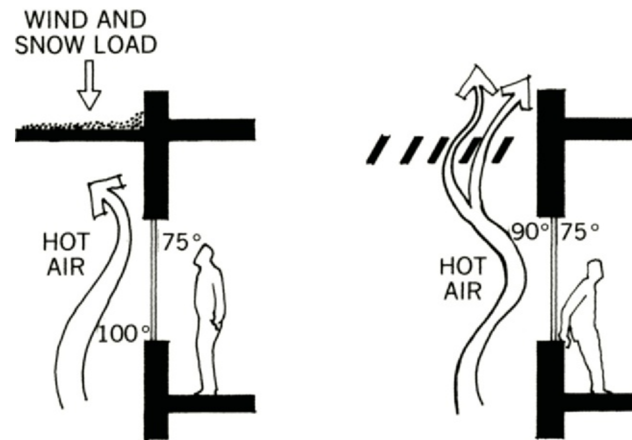


Figure 9.6a Horizontal louvered overhangs both vent hot air and minimize snow and wind loads. Also, their smaller-scale appearance is often desirable.

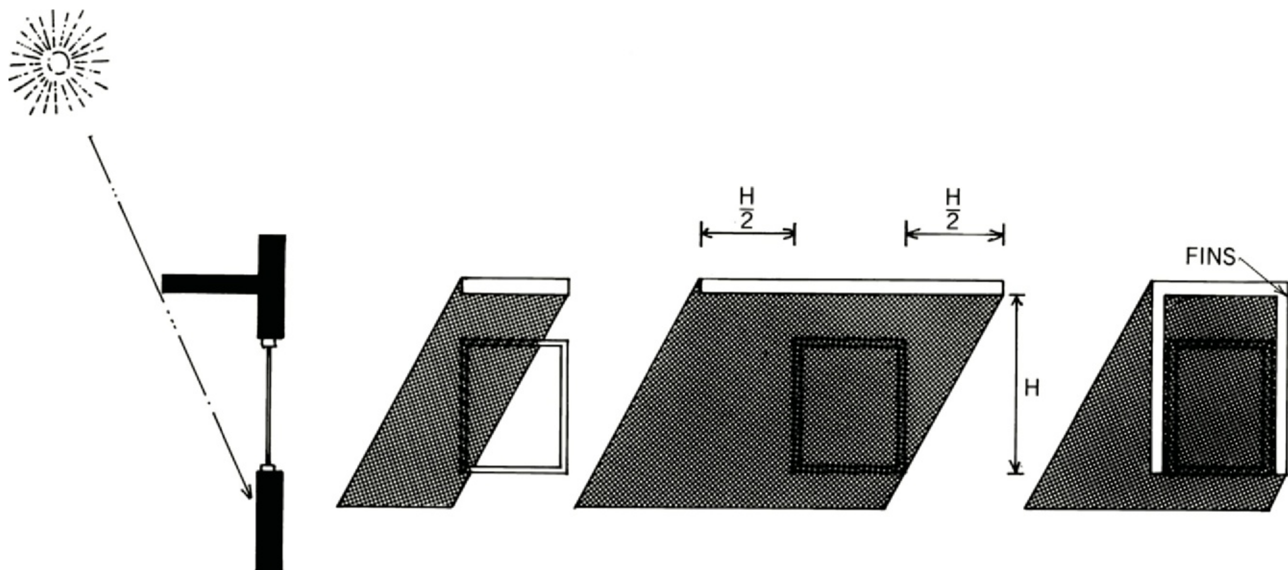


Figure 9.6b The sun easily outflanks any overhang the same width as the window. Use a wider overhang or vertical fins on each side of the window.

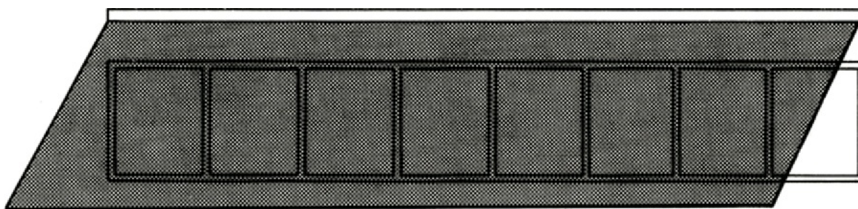


Figure 9.6c Wide strip windows make efficient use of the horizontal overhang.

Horizontal louvers have a number of advantages over solid overhangs. Horizontal louvers in a horizontal plane reduce structural loads by allowing wind and snow to pass right through (see Diagram II in Table 9.3). In the summer, they also minimize the collection of hot air next to the windows under the overhang (Fig. 9.6a). Horizontal louvers in a vertical plane (Diagram III in Table 9.3) are appropriate when the projecting distance from the wall must be limited as when a building is on or near the property line. Louvers are also useful when the architecture calls for small-scale elements that create a richer texture and a more humane scale.

When designing an overhang for the south facade, one must remember that the sun comes from the southeast before noon and from the southwest after noon. Therefore, the sun will outflank any overhang the same width as a window. Narrow windows need either a very wide overhang or vertical fins in addition to the overhang (Fig. 9.6b). Wide strip windows are less affected by this problem, as can be seen in Fig. 9.6c.

9.7 DESIGN OF HORIZONTAL OVERHANGS—BASIC METHOD

1. Find the date of the end of the overheated period (i.e., the last day that full shading is required) for envelope-dominated and internally dominated buildings from Tables 9.5B and 9.5C.
2. On a horizontal sun-path diagram for the appropriate latitude, darken the sun path that defines the end of the overheated period (Fig. 9.7a).
3. On this sun-path diagram, draw a line representing the orientation of the window through the center point (Fig. 9.7a).
4. Also through the center point, draw the sunray that is perpendicular to the window (Fig. 9.7b).
5. Find the point of intersection between the sunray and the sun path from step 2 above.
6. By means of this point, find the altitude angle and time of day of the sunray.
7. On a section of the window, draw the sunray to the windowsill (Fig. 9.7c).
8. Draw an overhang that reaches this sunray.
9. Extend the overhang a minimum distance of $H/2$ on each side of the window if fins are not used.

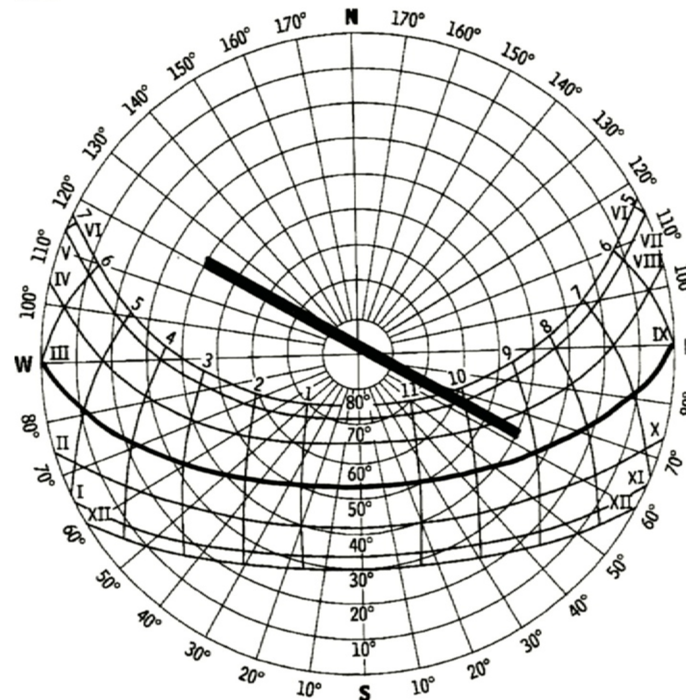


Figure 9.7a Highlight the sun path that represents the end of the overheated period. Draw the window orientation through the center of the diagram.

Example

Problem

Design a shading device for a window that is facing southwest at an azimuth of 120° (30° north of an east–west line). It is located at 36° N latitude in the city of Knoxville, Tennessee, in an envelope-dominated school.

Solution

Step 1. From Table 9.5C, the last day of the overheated period is about September 21 (use the closest 21st day of a month).

Step 2. On the horizontal sun-path diagram for 36°, darken the sun path for September 21 (Fig. 9.7a).

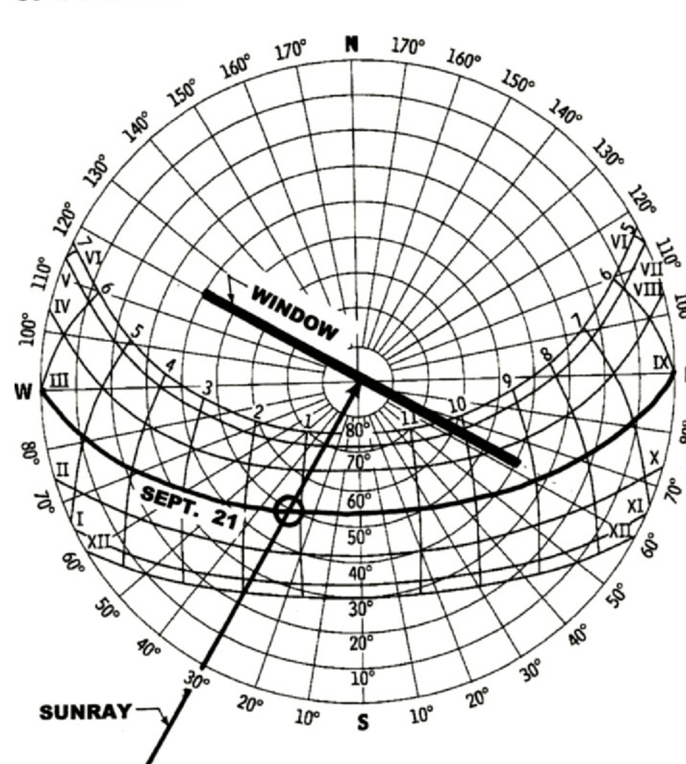


Figure 9.7b Draw the sunray that is perpendicular to the window at the center of the sun-path diagram. The altitude angle of this sunray can be determined from the point that results from the intersection of this sunray and the sun path that represents the end of the overheated period. From this point, it is also possible to determine the time of day when the sun is perpendicular to the window at this time of year.

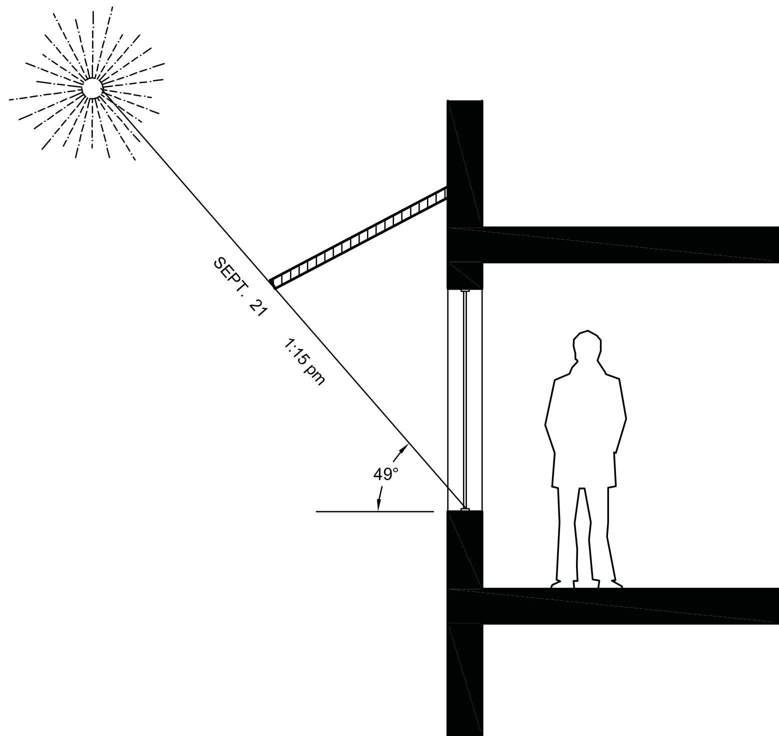


Figure 9.7c On a section draw the sunray from the windowsill. Any overhang that reaches this sunray will shade the window effectively the whole overheated period of the year.

Step 3. On this same sun-path diagram, draw the window through the center (Fig. 9.7a).

Step 4. Draw a sunray perpendicular to the window through the center of the sun-path diagram (Fig. 9.7b).

Step 5. Locate the intersection of the sunray and sun path, from which we can determine the altitude angle (49 degrees) and time of day (about 1:15) when the sun is perpendicular to the window.

Step 6. On a section of the window, draw the sunray at an altitude angle of 49° from the windowsill (Fig. 9.7c).

Step 7. Design an overhang that reaches this sunray (Fig. 9.7c). One of many possible solutions is shown.

Step 8. Extend the overhang a distance of $H/2$ on either side of the window, or add vertical fins on both sides, or a combination, as shown in Figure 9.7d.

Note: Because some climate regions are large, it is important to use the actual latitude of the building site if it is more than 2° different from the reference city. It may also be necessary to adjust the last day of the overheated period, especially if the building site is near a climate region boundary.

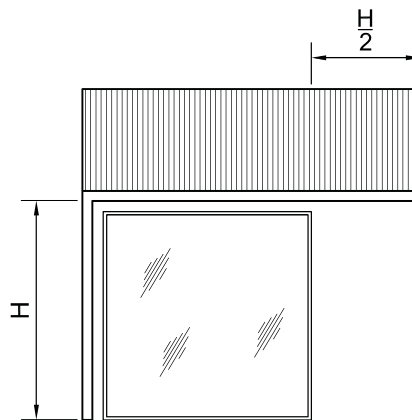


Figure 9.7d To prevent the sun from outflanking the overhang, in this example a vertical fin is used on the northwest side of the window and an overhang extension is used on the southeast side. This solution is asymmetric because the solar geometry is asymmetric in relation to this window.

9.8 SHADING DESIGN FOR SOUTH WINDOWS

For south windows, the first step is to decide on either a fixed or movable horizontal overhang. Use the following rules for this purpose.

Rules for Selecting a South Window Shading Strategy

1. If shading is the main concern and passive heating is not required, then a fixed overhang may be used.
2. If both passive heating and shading are important (long over- and underheated periods), then a movable overhang should be used.

The next step is to choose or design a particular kind of overhang. Refer to Tables 9.3 and 9.4 for examples of the generic types.

The size, angle, and location of the shading device can be determined by several different methods. The most powerful, flexible, and informative is the use of physical models. This method will be explained in detail in Section 9.17. There are also graphic methods, one of which was explained in the previous section. Finally, there are rules and design guidelines. Because this last method is the quickest and easiest, it is presented here in some detail. It must be noted, however, that this method is always limited in flexibility and application. The author, therefore, strongly recommends the use of physical models in conjunction with the design guidelines described below.

9.9 DESIGN GUIDELINES FOR FIXED SOUTH OVERHANGS

As stated in the rules above, a fixed horizontal overhang is most appropriate when passive solar heating is not desired. The goal, then, is to find the length of overhang that will shade the south windows until the last day of the overheated period.

Figure 9.9a shows the sun angle at the end of the overheated period.

Table 9.9A Sizing South Overhangs on Internally Dominated Buildings

Climate Region	Reference City	Angle A (Full Shade)	Angle B (Full Sun)
1	Hartford, CT	59	54
2	Madison, WI	58	47
3	Indianapolis, IN	53	47
4	Salt Lake City, UT	60	49
5	Ely, NE	69	59
6	Medford, OR	59	45
7	Fresno, CA	55	33
8	Charleston, SC	54	36
9	Little Rock, AK	54	43
10	Knoxville, TN	53	41
11	Phoenix, AZ*	48	NA
12	Midland, TX	52	40
13	Fort Worth, TX	54	41
14	New Orleans, LA*	49	NA
15	Houston, TX*	49	NA
16	Miami, FL*	40	NA
17	Los Angeles, CA*	33	NA

Notes:
This table is for south-facing windows or windows oriented up to 20° off south.
An overhang reaching the full shade line will shade a window for most of the overheated period.
An overhang not projecting beyond the full sun line will allow full solar exposure of a window for most of the underheated period.
*Use a fixed overhang projecting to the full shade line, because passive solar heating is not required in these climates for internally dominated buildings.

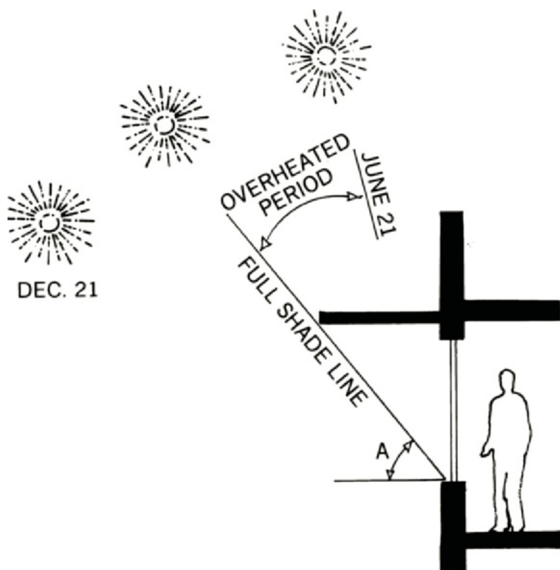


Figure 9.9a The full shade line determines the length of overhang required for shade during the overheated period.

Since the sun is higher in the sky during the rest of the overheated period, any overhang that extends to the line shown will fully shade the window for the whole overheated period. This full shade line is defined by angle A and is drawn from the windowsill. This angle is given for each reference city in the seventeen climate regions in Table 9.9A for internally dominated buildings and in Table 9.9B for envelope-dominated buildings.

Overhangs that are higher on the wall and that extend to the full shade line will still block the direct radiation and yet give a larger view of the sky. However, this would not be desirable in regions with significant diffuse radiation, since both increased overheating and visual glare will result from the increased exposure to the bright sky (Fig. 9.9b). Even the overhang shown in Figure 9.9a might not be sufficient in very humid regions, where over 50 percent of the total radiation can come from the diffuse sky. Rather than increasing the length of the overhang or slanting it down, it might be desirable to use other devices, such as curtains or plants, to block the diffuse radiation from the low sky.

Although any fixed overhang designed by the above guidelines or the basic method (Section 9.7) will provide full shade until the last day of the overheated period, there will be excessive shading in the winter. See again Figures 9.4a, b, and c, which illustrate how much of the winter sun is blocked by a fixed overhang.

Furthermore, an overhang extending to the full shade line can result in a quite dark interior. If daylighting is desired, as is often the case, then the strategies of Chapter 13 should be followed. The techniques described there allow ample light to enter a building while minimizing the overheating effect.

Procedure for Designing Fixed South Overhangs

1. Determine the climate region of the building from Figure 5.5.
2. Determine angle A from Table 9.9A for internally dominated and from Table 9.9B for envelope-dominated buildings.

Table 9.9B Sizing South Overhangs on Envelope-Dominated Buildings

Climate Region	Reference City	Angle A (Full Shade)	Angle B (Full Sun)
1	Hartford, CT	65	59
2	Madison, WI	64	55
3	Indianapolis, IN	63	55
4	Salt Lake City, UT	65	60
5	Ely, NE	72	69
6	Medford, OR	71	61
7	Fresno, CA	64	45
8	Charleston, SC	65	49
9	Little Rock, AK	63	52
10	Knoxville, TN	62	51
11	Phoenix, AZ	56	49
12	Midland, TX	63	50
13	Fort Worth, TX	61	54
14	New Orleans, LA	63	44
15	Houston, TX	60	42
16	Miami, FL*	50	NA
17	Los Angeles, CA	61	43

Notes:
This table is for south-facing windows or windows oriented up to 20° off south.
An overhang reaching the full shade line will shade a window for most of the overheated period.
An overhang not projecting beyond the full sun line will allow full solar exposure of a window for most of the underheated period.
*Use a fixed overhang projecting to the full shade line because passive solar heating is not required in this climate.

3. On a section of the window, draw the full shade line from the windowsill.
4. Any overhang that extends to this line will give full shade until the last day of the overheated period of the year.
5. Slightly shorter overhangs would still be useful, even though they would shade less of the overheated period.

Note: This guideline method can only be used for windows within 20° of south that are located in or near a reference city. For other south windows use the basic method of Section 9.7.

9.10 DESIGN GUIDELINES FOR MOVABLE SOUTH OVERHANGS

The design of movable overhangs is the same as for fixed overhangs for the overheated period of the year. However, to make effective use of passive solar heating, the overhang must retract to avoid shading the window during the underheated period.

To ensure full sun exposure of a window during the underheated period (winter), two points must be addressed. The first is to determine by which times of year the overhang must be retracted, and the second is to determine how far it must be retracted.

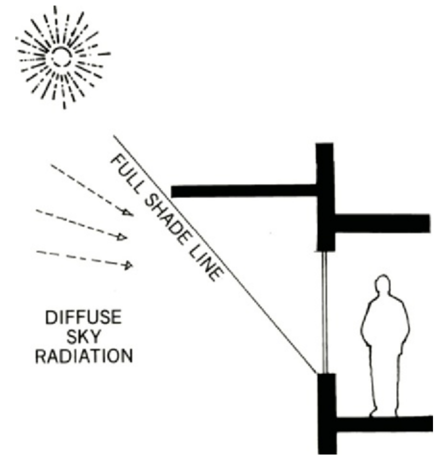


Figure 9.9b Fixed overhangs placed higher on the wall are not desirable in humid climates, because of the large amount of diffuse radiation and glare.

The simplest and most practical approach to the first question is to extend and retract the shading device during the spring and fall transition periods. These periods are described in Tables 9.5B and 9.5C. Making the twice-annual changeover could be no more complicated than washing the windows and could be done at the same time.

The sun angle at the end of the underheated period (i.e., the last day of the underheated period on which full solar exposure is still desired) determines the full sun line (Fig. 9.10a). Since the sun is lower than this position during the rest of winter, any overhang short of this line will not block the sun when it is needed. This full sun line is defined by angle B and is drawn from the window's head. The approximate angle is given for each climate region in Tables 9.9A and 9.9B.

Procedure for Designing Movable South Overhangs

1. Determine the climate region of the building from Figure 5.5.
2. Determine angles A and B from Table 9.9A for internally dominated buildings and from Table 9.9B for envelope-dominated buildings.
3. On a section of the south window, draw the full shade line (angle A) from the windowsill, and draw the full sun line (angle B) from the window head (Fig. 9.10b).
4. A movable overhang will have to extend to the full shade line during the overheated portion of the

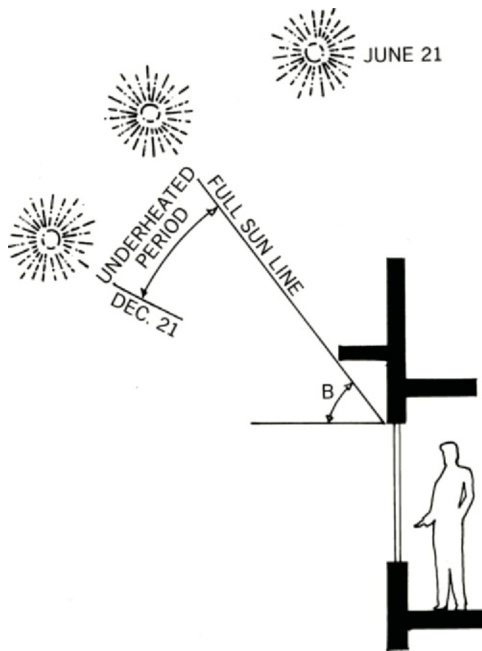


Figure 9.10a The full sun line determines the maximum allowable projection of an overhang during the winter period.

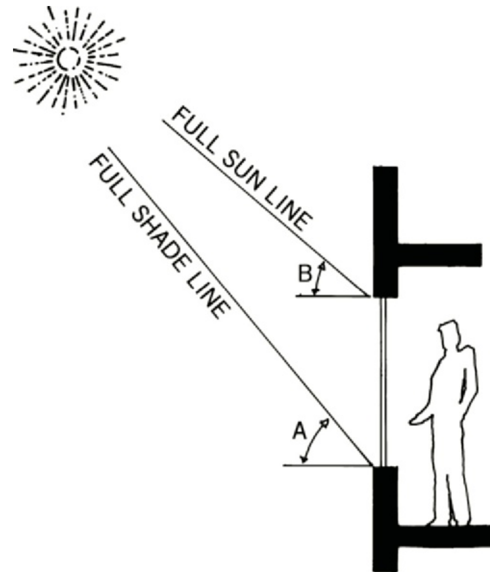
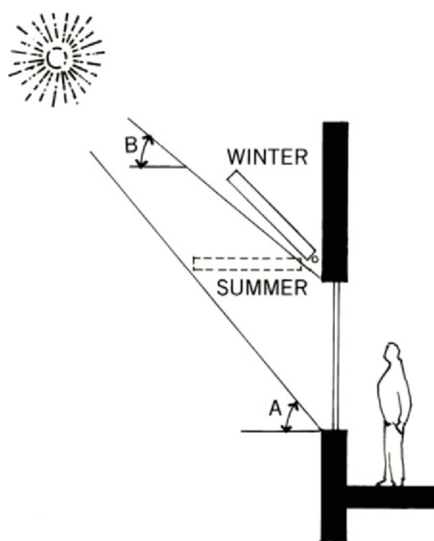


Figure 9.10b A fixed overhang, unlike a movable overhang, will not work well because it cannot both meet the full shade line and stay behind the full sun line.



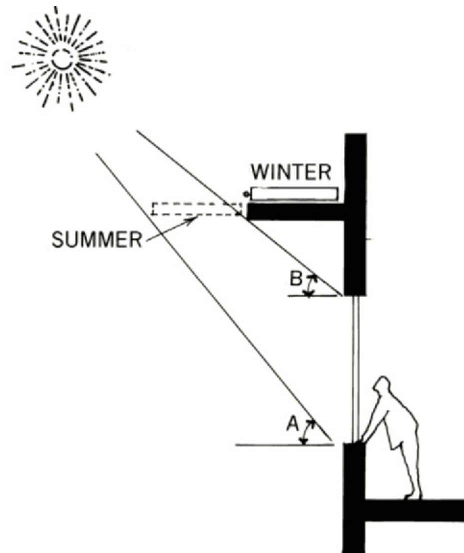


Figure 9.10c Two alternative movable overhangs are shown in both the winter (underheated) and the summer (overheated) positions. Of course, awnings are the most common movable shading device.

year and not extend beyond the full sun line during the underheated period of the year. See Figure 9.10c for two of many possible solutions.

5. The overhang should be extended during the spring transition period and retracted during the fall transition period. The dates for these transition periods can be determined from Table 9.5B for internally dominated and Table 9.5C for envelope-dominated buildings.

Note: This guideline method can only be used for windows within 20° of south that are located in or near a reference city. For other south windows use the basic method of Section 9.7.

When using the basic method of Section 9.7 for designing a movable overhang, repeat the steps for finding the full shade line to also find the full sun line. That line drawn from the head of the window will determine the maximum that the overhang can project during the underheated part of the year to give full access to the winter sun.

9.11 SHADING FOR EAST AND WEST WINDOWS

For the east and west orientations, unlike the south, it is not possible to fully shade the summer sun with a fixed overhang, and Figure 9.11a shows how futile it would be to try. The only way to completely shade east or west

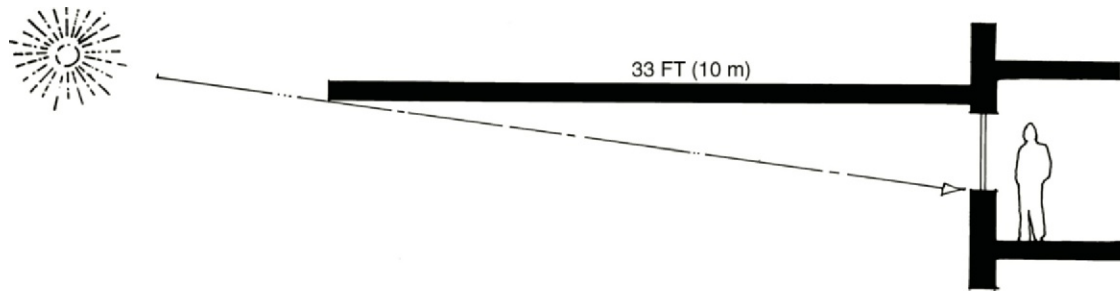


Figure 9.11a The 33 ft (10 m) overhang needed to shade a 4 ft (1.2 m) window on August 21 at 6 P.M. at 36° N latitude illustrates the futility of trying to fully shade east and west windows with fixed horizontal overhangs.

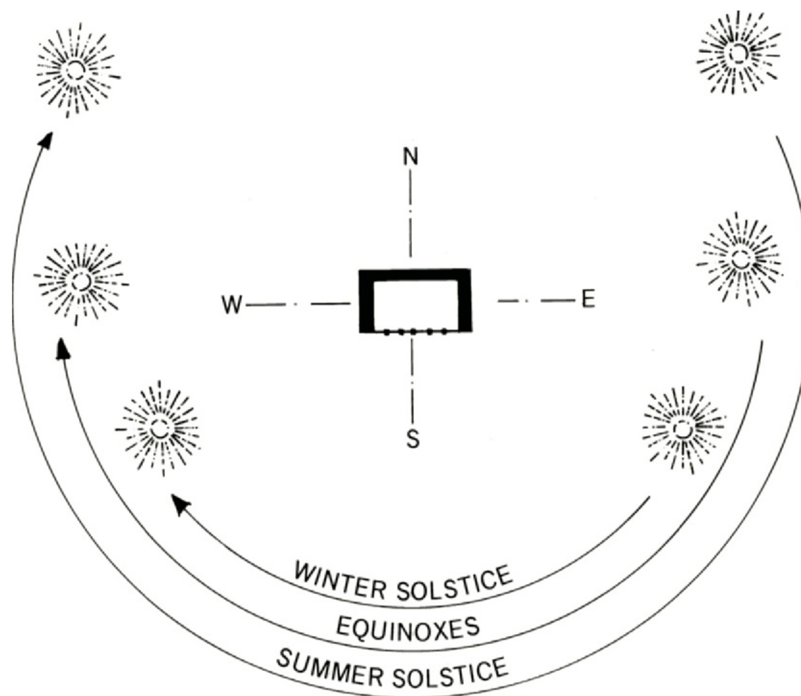


Figure 9.11b This plan view illustrates the sweep of the sun's azimuth angle at different times of the year from sunrise to sunset.

windows is with a vertical opaque device like a shutter that also blocks the view. The goal for east and west windows, therefore, is to shade as long as possible while maintaining the view.

Since an overhang cannot fully shade east and west windows, it was assumed the vertical fins would be a better option. In fact, vertical fins shade no better than horizontal overhangs, and they obstruct the view much more. Figure 9.11b illustrates the fact that there is a period every morning and afternoon when the sun shines directly at the east and west facades during the summer six months of the year (March 21 to September 21). Therefore, vertical fins that face directly east or west will allow too much sun penetration every day during the summer. To minimize this solar penetration, the exposure angle must be decreased by a more narrow spacing of the fins, by making the fins deeper, or both (Fig. 9.11c). To be highly effective, the fins must be so deep and so closely spaced that a view through them becomes almost impossible. Consequently, vertical fins are not a good solution on the east and west facades.

The problem with vertical fins is much worse than the horizontal exposure angle shown in Figure 9.11c would suggest. In the summer morning and afternoon, the sun's motion is as much vertical as horizontal. Consequently, the sun spends much more time in the exposure angle than a plan view would indicate. This problem is very obvious when vertical fins are tested with a heliodon where the sun's motion is seen in three dimensions or when looking at real windows protected by fins in the summer (Fig. 9.11d).

Another problem with vertical fins is that they reflect light into a building to the right and to the left while for quality daylight, the light should be reflected up through the window so that it is reflected off the ceiling.

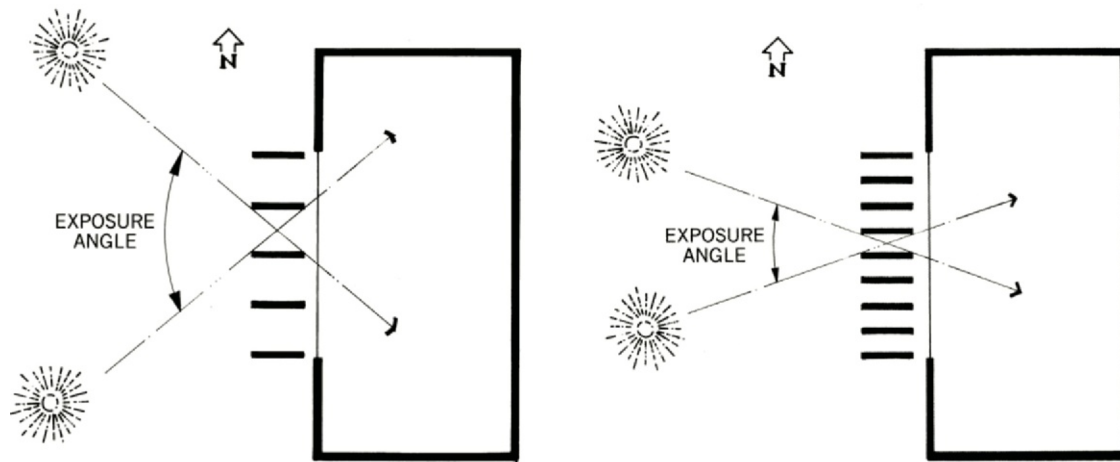


Figure 9.11c A plan view of vertical fins on a west (east) facade illustrates how solar penetration is reduced by moving fins closer together, by making them deeper, or both.

Thus, horizontal louvers are far superior to vertical fins.

Vertical fins are not good for shading east and west windows!

Slanted fins, however, can be appropriate especially when there is a desire to control the direction of view. To block the view to the west, fins could be slanted to the northwest or to the southwest for more winter sun.

By moving in response to the daily cycle of the sun, movable fins allow somewhat unobstructed views for most of the day and yet block the sun when necessary. For example, movable fins on a west window would be held in the perpendicular position until the afternoon, when the sun threatened to outflank them (Fig. 9.11e, top). Either at once or gradually, they would then rotate to the position shown in Figure 9.11e (middle). When the sun starts to outflank that position, the fins quickly rotate to the position shown in Figure 9.11e (bottom). Finally, when the sun has set, the fins rotate into the position ready for the next day as shown in Figure 9.11e (top).

Movable vertical fins can provide more shade and view than fixed fins, but still not as much as a movable overhang. Since the view is usually the top priority, even moveable fins are not recommended on the east and west windows.

As mentioned before, the best strategy is to avoid east and west windows whenever possible. If that is not possible, minimize the number of windows and orient them in a "landscape" rather than "portrait" mode, because short windows are easier to shade than tall windows (Fig. 9.11f). An overhang about as deep as a short west window is high could maintain the view and shade the high sun until about 4 P.M. After 4 P.M., the shading system would adjust or be supplemented to keep blocking the sun with the recognition that the view would then be lost all at once or gradually until the sun has set.

A similar solution could use a movable overhang made of a very low solar transmission glass (Fig. 9.11g). It would first act as a horizontal overhang and then rotate down into a vertical position as the afternoon progressed. However, even when it completely covers the glass it would still allow for a view even if somewhat dark.

The Bateson office building uses a different strategy consisting of exterior roller shades to maximize the view while fully shading the direct sun (see again Fig. 9.4k). In the morning, the east shades are down and west shades are up, providing an unobstructed view to the west. In the afternoon, the east shades are up and the west shades slowly move down to always just block the sun. In the late afternoon, the west shades are completely extended, completely blocking the view. Note, however, that the solutions with overhangs provide an unobstructed view for a longer time. Thus, an overhang on the east and west is the best choice even though that contradicts the widely held belief that vertical fins should be used there.

Shading east and west windows becomes practical if there are large buildings or trees shading the low sun. In that case, only a simple but deep overhang will provide full shade with a view of the buildings or trees. For low rise buildings and given sufficient property, trees could be planted to protect the east and west facades. Because it will take many years before the trees produce effective shade, some other shading system needs to be used in the interim.

Rules for East and West Windows

1. Use as few east and especially west windows as possible.
2. Have windows on east or west facades face north or south, as shown in Figure 9.3b.



Figure 9.11d This photo of west facing windows was taken on a summer afternoon. The lack of shading by the vertical fins is proof of their impotence. Fins are not effective shading devices on east and west windows!

3. Use horizontal rather than vertical windows (i.e., use short windows).
4. Since views of the ground and horizon are usually important, use a horizontal overhang with a backup movable shading device.
5. Horizontal louvers are better than vertical fins in part because they support quality daylighting.
6. Use trees, plant-covered trellises, or hanging plants (Figs. 9.4g–9.4i).
7. If views to the east or west are not desirable, slanted vertical fins can be an alternative. Slant the fins toward the northwest if shading is required most of the year. Slant the fins toward the southwest if winter sun is desired.
8. Use movable shading devices for both better shading and better views.

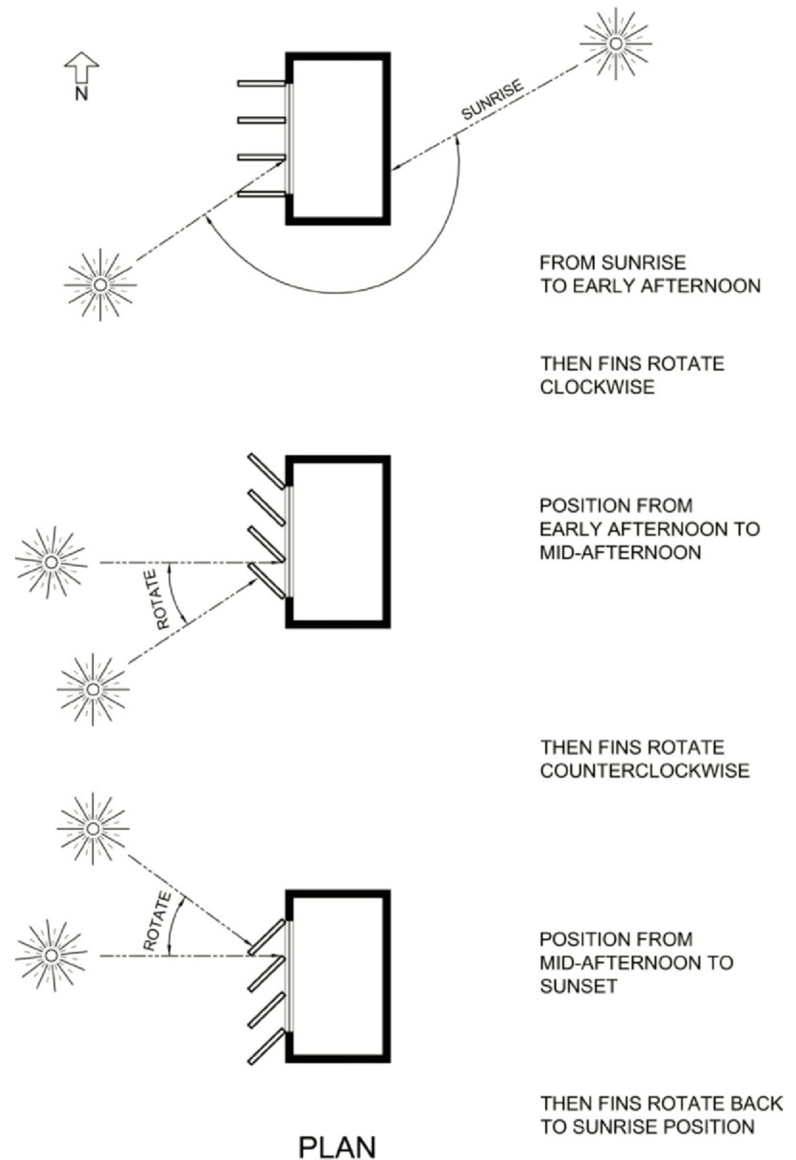


Figure 9.11e Movable fins would be in their maximum open position until the sun is about to enter. At that time, the fins would rotate to block any direct sunlight (middle). Before they are outflanked again, they rotate to the position shown at the bottom. At sunset, they would rotate back to the maximum open position.

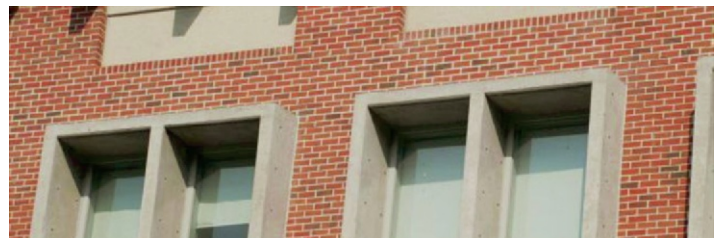


Figure 9.11f Since the depth of an overhang is a function of the height of a window, short window will require less deep overhangs.

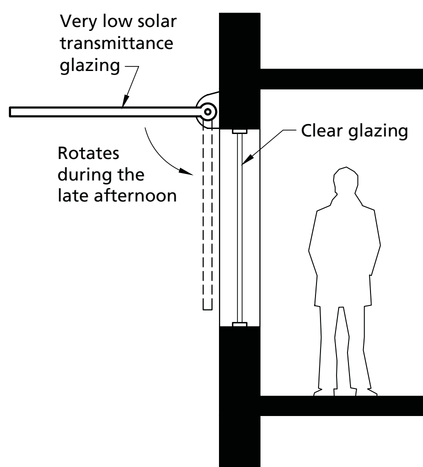


Figure 9.11g One option for shading east and west windows consists of using a very low solar transmission glazing that acts as an overhang when the sun is high and turns into "sunglasses" when the sun is low.

9.12 DESIGN OF EAST AND WEST HORIZONTAL OVERHANGS

When views to the east and west are desirable, use horizontal overhangs. A long overhang can be reasonably effective while giving a better view of the landscape than do vertical fins. Although there is a fair amount of time when the sun peeks under an east and west overhang, there are many hours of useful shade. In most cases, horizontal overhangs are better than vertical fins for east and west orientations.

When the sun peeks under the overhang, additional shading should be provided, and if at all possible the additional shading should be on the exterior. If that is not possible, then use indoor shading in the form of venetian blinds, roller shades, drapes, etc. The increasingly popular option of low solar transmission glazing will be discussed in detail in Section 9.18 below.

Table 9.12 allows the designer to determine the length of overhang needed to shade east and west windows from 8 A.M. to 4 P.M. (solar time) during most of the overheated period. The length of overhang thus determined should be a guide rather than a rigid requirement. Shorter overhangs, although less effective, are still worthwhile.

The absurdly long overhangs required in hot climates, as indicated by Table 9.12, indicate the problem with east and west windows. It is, therefore, worth repeating once more that east and west windows should be avoided if at all possible in hot climates.

Procedure for Designing East and West Fixed Overhangs

1. Determine the climate region from Figure 5.5.
2. Determine angle C from Table 9.12.
3. On a section of the east or west window, draw the shade line from the windowsill.
4. Any overhang that projects to this line will shade east and west

Table 9.12 Sizing East and West Horizontal Fixed Overhangs

Climate Region	Reference City	Angle C: Internally Dominated	Angle C: Envelope Dominated
1	Hartford, CT	30	34
2	Madison, WI	30	34
3	Indianapolis, IN	25	32
4	Salt Lake City, UT	30	33
5	Ely, NE	34	36
6	Medford, OR	30	37
7	Fresno, CA	25	30
8	Charleston, SC	23	29
9	Little Rock, AK	24	29
10	Knoxville, TN	23	29
11	Phoenix, AZ	19	24
12	Midland, TX	22	28
13	Fort Worth, TX	23	28
14	New Orleans, LA	19	27
15	Houston, TX	19	25
16	Miami, FL	14	19
17	Los Angeles, CA	9	28

Notes:
Any overhang that extends to the shade line defined by angle C will shade east and west windows from 8 A.M. to 4 P.M. during most of the overheated period. Choose the column for angle C according to the building type (internally or envelope dominated). The extremely long overhang required in hot climates indicates the problem of shading east and west windows.

windows from 8 A.M. to 4 P.M. during most of the overheated period.

5. If the size of the recommended overhang is excessively long, use the largest one possible. The actual overhang size is not critical because an additional shading system is required for the time that the sun peeks under the overhang both early morning and late afternoon. The easiest backup shading systems are indoor blinds or shades, but systems on the exterior perform much better.

9.13 DESIGN OF FINS ON NORTH WINDOWS

Buildings with long overheated periods may also require shading of north windows. Because of the sun angles involved, small vertical fins are often sufficient. Figure 9.13 illustrates how the fins are determined by angle D from Table 9.13.

Procedure for Designing North Fins

1. Find the latitude of the building site from Figure 5.6d.
2. From Table 9.13, determine the appropriate angle D.
3. On a plan of the north window, draw the shade line at angle D from one side of the window (Fig. 9.13, left).

Table 9.13 Shade Line Angle for North Fins

Latitude	Angle D
24	18
28	15
32	12
36	10
40	9
44	8
48	7

4. Draw vertical fins to meet this shade line, and note that if intermediate fins are used, all fins will be shorter (Fig. 9.13 right).
5. Remember that fins are required on both the east and west sides of north windows.
6. To prevent the high sun from outflanking the top of the fins, add an overhang as deep as the fins.

9.14 DESIGN GUIDELINES FOR EGGCRATE SHADING DEVICES

Eggcrate shading devices are mainly for east and west windows in hot climates and for the additional southeast and southwest orientations in very hot climates. An eggcrate is a combination of horizontal overhangs (louvers) and vertical fins. By controlling sun penetration by both the altitude and azimuth angle of the sun, very effective shading of windows can be achieved. The view, however, is usually very obstructed.

The brise-soleil, developed by Le Corbusier, is an eggcrate system with dimensions frequently at the scale of rooms (see Figs. 9.1j and 9.1k). Since shading is a geometric problem, many small devices are equivalent to a few large ones (see Fig. 9.3g). Therefore, eggcrates can also be made at the scale of a fine screen. In India these screens were often cut from a single piece of marble (Fig. 9.14a). Today, these screens are most often made of metal (Fig. 9.14b) or masonry units (Fig. 9.14c). The shading effect of eggcrates at different scales is identical, but the view from the inside and the aesthetic appearance from the outside vary greatly.

The designer should first decide on the general appearance of the eggcrate system. The required dimensions of each unit (Fig. 9.14d) are best determined experimentally by means of a heliodon. As far as sun penetration is concerned, the scale of the eggcrate can be changed at any time as long as the ratios of h/d and w/d are kept constant. The use of the heliodon for this purpose will be explained in detail below.

The author does not recommend small-scale eggcrate shading if either a view or light is desired. Use such systems only where ventilation or security is the main objective.

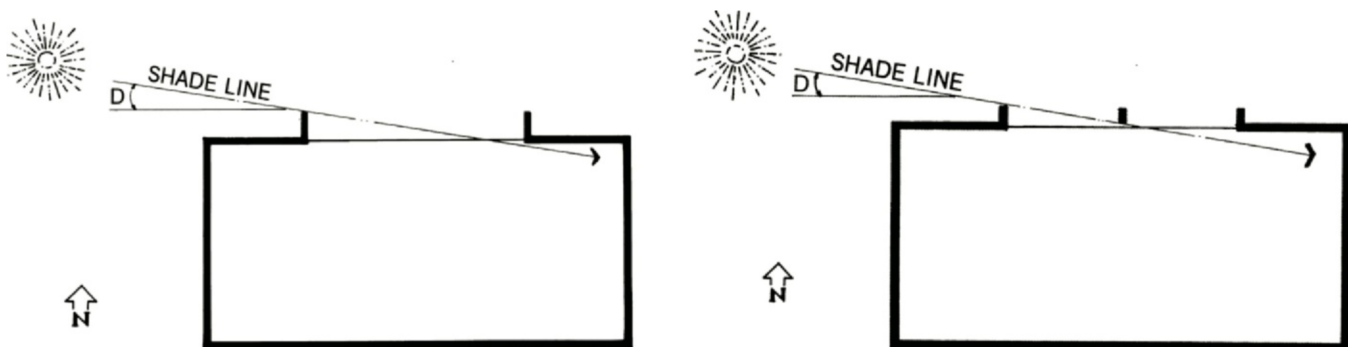


Figure 9.13 The shade line at angle D determines the vertical-fin design on north windows. An alternative solution is also shown.

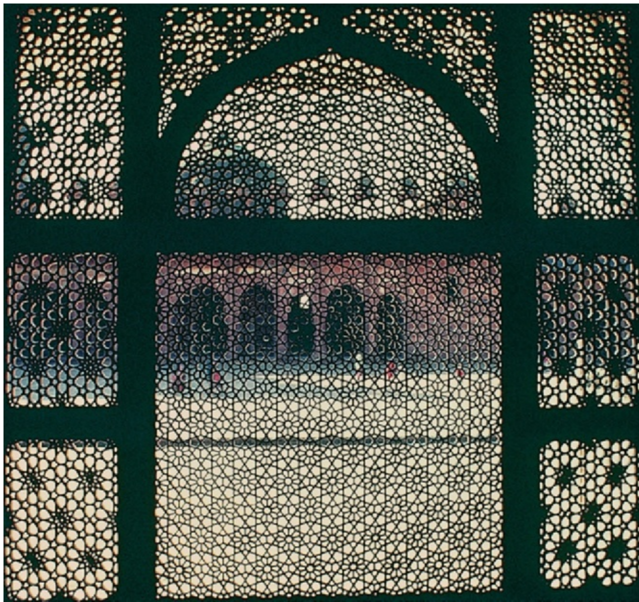


Figure 9.14a This marble screen, carved from a single piece of stone, is actually a miniature eggcrate shading device. The thickness of the slab is critical. The same pattern in a flat metal plate would be practically useless as a shading device. (Photograph by Suresh Choudhary.)

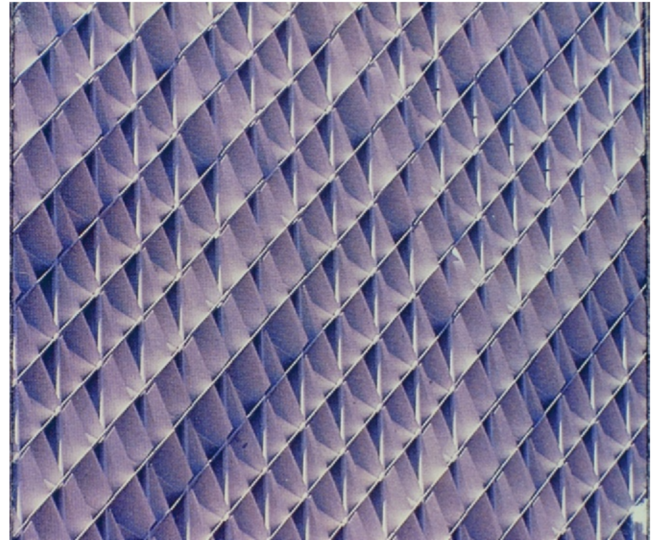


Figure 9.14b An eggcrate shading device made of metal. (Courtesy of Construction Specialties, Inc.)



Figure 9.14c Small and medium-sized eggcrate shading systems severely block the view. Medium to large eggcrate systems are usually made of concrete, while small eggcrates are often made of masonry units.

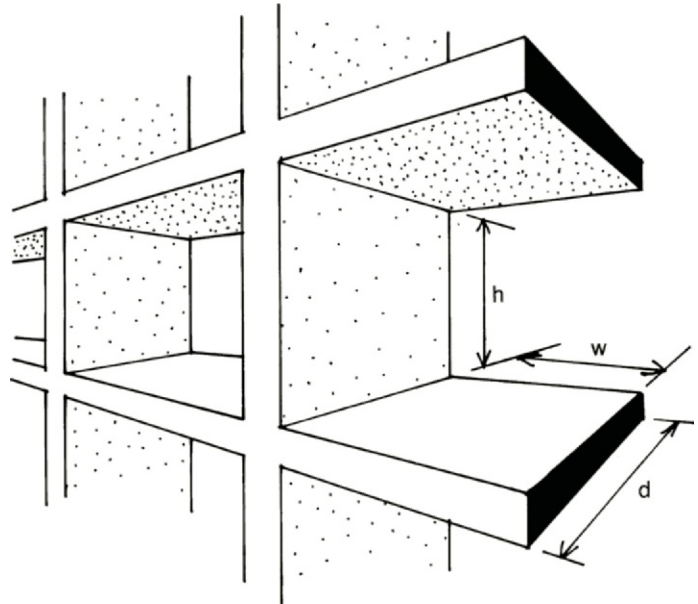


Figure 9.14d The shading effect is a function of the ratios *h*/*d* and *w*/*d*. It is not a function of actual size.

9.15 SPECIAL SHADING STRATEGIES

Most external shading devices are variations of the horizontal overhang, vertical fin, or eggcrate. However, some interesting exceptions exist.

The geodesic dome designed by Buckminster Fuller for the U.S. Pavilion at Expo '67 created an artificial climate for the structures within (Fig. 4.2b). To prevent overheating inside the clear plastic dome, the upper panels had vents and special roller shades. Each glazed hexagonal structural unit had six triangular roller shades operated by a servomotor. Figure 9.15a shows these shades in various positions.

A completely different approach is to rotate the building with the changing azimuth of the sun. If this sounds far-fetched, consider the fact that rotating buildings have already been built. To enjoy the beautiful panoramic view of his Connecticut property, Richard Foster built a revolving house (Fig. 9.15b).

A rotating building specifically designed for its solar benefits is the Heliotrope built in Freiburg, Germany, by the architect Rolf Disch as his home (Figs. 9.15c and 9.15d). The building, like a heliotrope flower, tracks the sun. In the winter, the triple-glazed windows face the sun, while in the summer the building exposes its blank insulated wall to the hot sun. The balcony railing consists of vacuum-tube solar hot-water collectors. Rotating separately on the roof, the PV array generates much more electricity than the building needs. Thus, the Heliotrope is better than a zero-energy building—it is an energy-plus house.

A similar but simpler approach would be to have the building stand still but a shade move around it. For example, a barn door hanging from a curved track could follow the sun around a building (Fig. 9.15e). If the barn door were covered with PV cells, you would have a tracking solar collector as well. Or the barn door could be made of darkly tinted glazing so that the building always has "sunglasses" facing the sun in the summer.

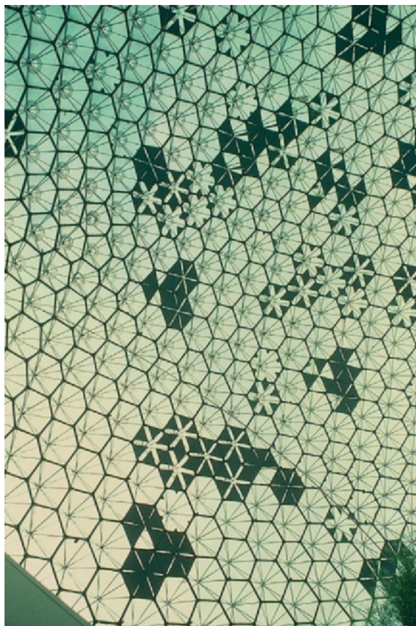


Figure 9.15a The U.S. Pavilion, Expo '67, Montreal, Canada, was designed by Buckminster Fuller. This view of the dome from the inside shows the vent holes and triangular roller shades that prevent overheating in the summer.



Figure 9.15b The residence that architect Richard Foster built for himself in Wilton, Connecticut, in 1967 is round and rotates 360° to take full advantage of the panoramic view and passive solar heating. (Courtesy of Richard Foster, architect.)



Figure 9.15c Architect Rolf Disch of Freiburg, Germany, has designed his home to track the sun. His Heliotrope house rotates to face welcoming windows toward the winter sun and a blank wall to intercept the summer sun. The PV panels on the roof rotate separately to always collect the maximum solar radiation. (Courtesy of architect Rolf Disch.)

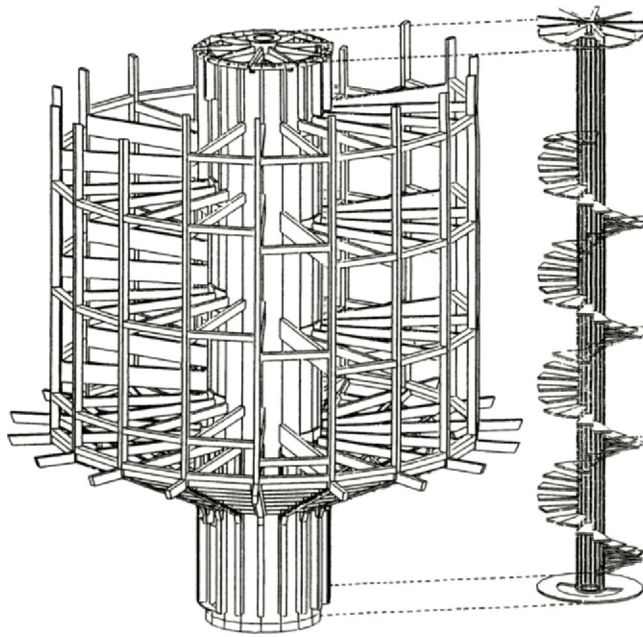


Figure 9.15d A section of the rotating solar house called the Heliotrope. (Courtesy of architect Rolf Disch.)

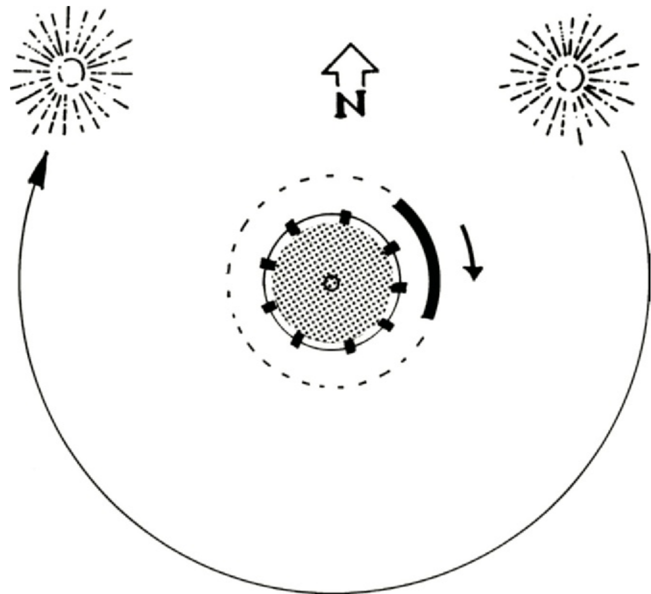


Figure 9.15e A shading panel can rotate around the building in phase with the sun. If the panel is covered with PV, it also acts as a tracking solar collector.

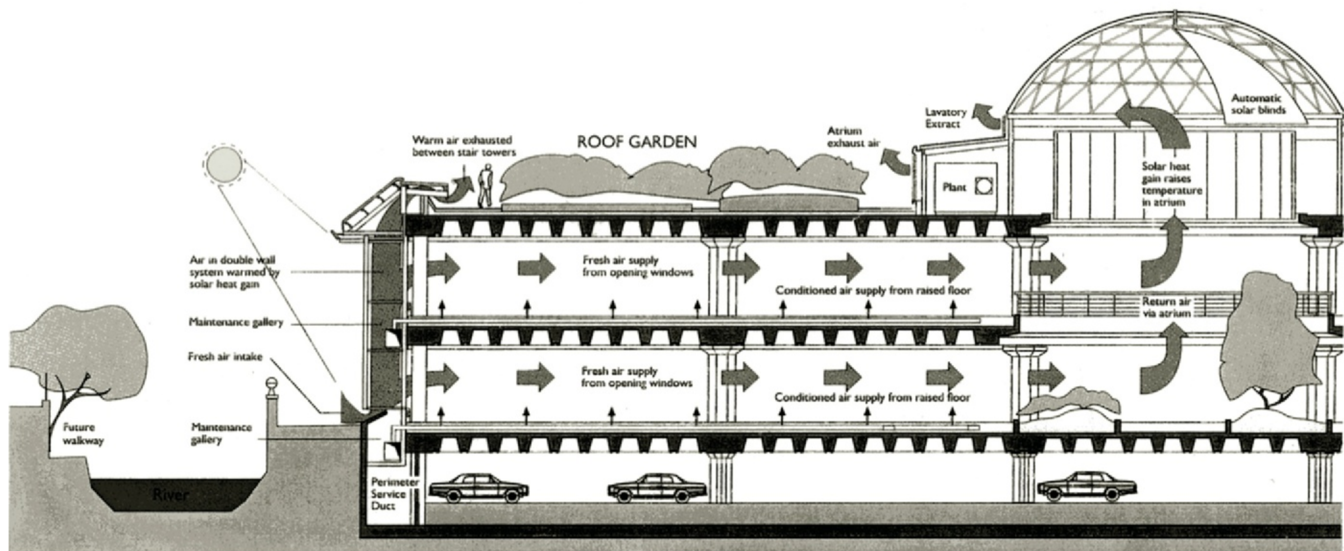


Figure 9.15f The Tanfield House in Edinburgh, Scotland, designed by Michael Laird Partners, uses domes to daylight and ventilate the atria. To prevent overheating, triangular solar blinds rotate when needed on indoor tracks to block the sun. (Tanfield House, Edinburgh—Michael Laird Architects.)

Instead of sunglasses, the Tanfield House uses a triangular parasol to shade its glass domes. The solar blind is a spherical triangle that moves on an indoor circular track in order to block the sun when appropriate (Fig. 9.15f). The domes are used for daylighting, natural ventilation, and space heating.

The architect of the Indian Heritage Center in New Delhi, India, decided that the best way to shade not only the windows but also the walls and the land between buildings would be to have a shade structure spanning between buildings (Fig. 9.15g). The space-frame supported shading allows wind, rain, and hot air to pass through. The shading simulates the functional and aesthetic benefits of a very high canopy of trees.

The Singapore Concert Hall uses triangular sun shields (caps) to keep the direct sun from entering the glass-covered buildings (Fig. 9.15h).



Figure 9.15g The Indian Heritage Center uses shading that spans from building to building in response to the very hot climate of New Delhi, India. The shading structure shades the windows, walls, and the land between the buildings.



Figure 9.15i This parasol roof in Singapore shades both the actual roof and the roof garden.

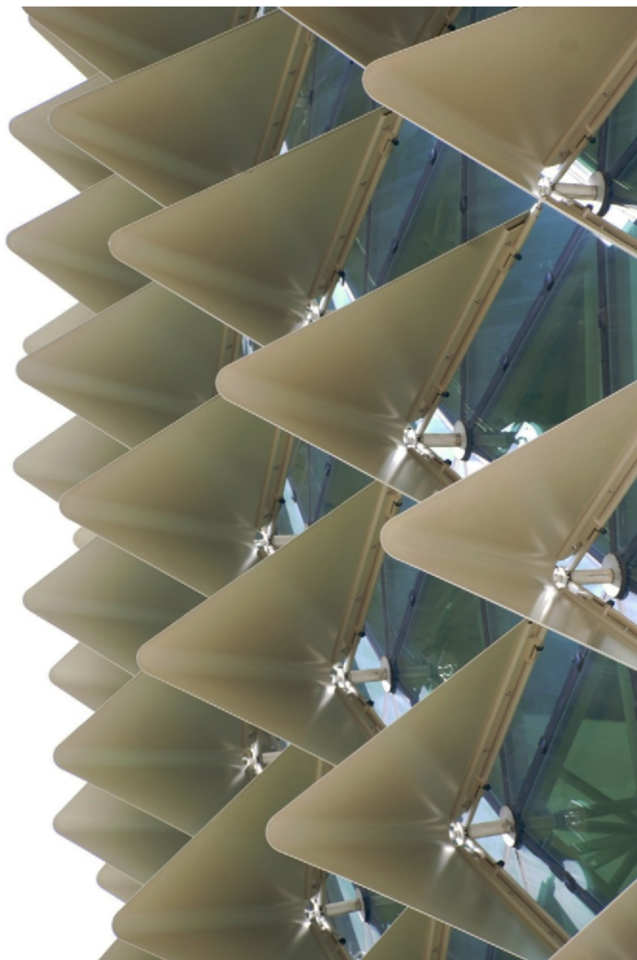


Figure 9.15h The glass dome of the Singapore Concert Hall is covered with aluminum caps to keep out the direct sun.

For buildings with a flat roof, a parasol roof, as Le Corbusier called it, will shade not only the roof but people enjoying a roof garden (Fig. 9.15i).

The use of outdoor meshes and screens is an increasingly popular method of shading and decorating buildings. When the mesh is very fine like an insect screen, the view is mostly unobstructed. However, if the mesh or screen is fixed, it will shade the winter sun just as much as the summer. It is not selective like an overhang or louvers.

9.16 SHADING OUTDOOR SPACES

Shading of outdoor spaces can be just as important as shading buildings. Open-air amphitheaters and stadiums are a special problem because of their size and need for unobstructed sightlines. The most popular solution is the use of membrane tension structures, since they can span large distances at relatively low cost. Most often, waterproof membranes are used because they also protect against rain (Fig. 9.16a), but in dry climates, an open-weave fabric might be more appropriate. This is not a new idea, however, for the Romans covered not only their theaters but even their gigantic Colosseum with an awning (Fig. 9.16b). The toldo, or pleated awning, is a similar device traditional in parts of the Islamic world, Spain, and parts of Central America for covering courtyards and narrow streets. Because of its functionality and beauty, it is increasingly popular in the United States (Figs. 9.16c–e).

Many traditional shading structures were designed to create shade while letting air and rain pass right



Figure 9.16a The public areas in this outdoor mall in Las Vegas are shaded by translucent membrane tension structures.

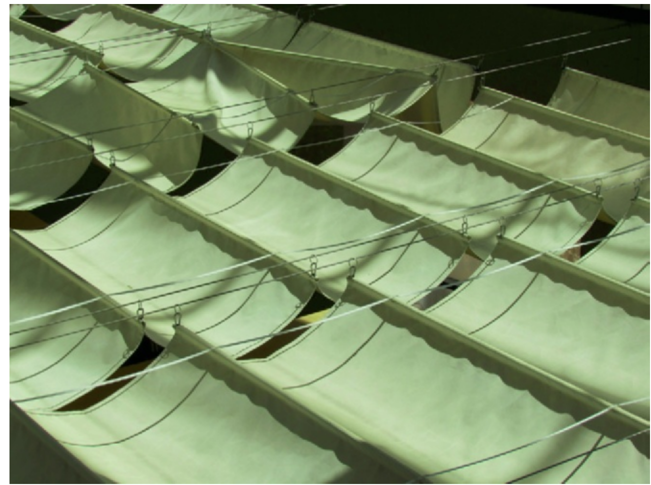


Figure 9.16c The toldo (pleated awning) is a beautiful and effective device for shading outdoor spaces. It can be easily retracted along its horizontal support cables at night, when it is cloudy or stormy, and when it is no longer hot.



Figure 9.16b The Roman Colosseum, which was built about A.D 80 and seated about 50,000 spectators, was covered with a giant awning for sun protection. (From *Lanfiteatro Flavio Descritto e Deliniato*, by Carlo Fontana, Vaillant, 1725.)

through. The pergola, trellis, and arbor are examples of such structures (Figs. 9.16f–h). Pergolas without plants must be carefully designed if they are to provide effective shading. The typical pergola shown on the left in Figure 9.16i provides little shade when it is needed most—around the noon hours. Pergolas should have the beams (louvers) tilted toward the north in order to create meaningful shade in the summer (Fig. 9.16i, right). Interesting nontraditional shading structures are shown in Figures 9.16j–l.

When the outdoor shading system is fixed and permanent, it should be designed to let the winter sun enter while rejecting the summer sun (Fig. 9.16m). The author has seen many shading structures that created more shade in the winter than in the summer. Designing a successful shading structure is not as simple as it might seem. The best way to design a shading system for an outdoor space as well as for a building is to use physical models on a heliodon. This technique will now be explained.



Figure 9.16d In this unusual instance, the toldo protects an indoor space in the Salt Lake City central library.



Figure 9.16e This winter garden in Washington, D.C., is protected from the summer sun by folding awnings also known as toldos. In this case, the shading is on the indoor side of the glazing.

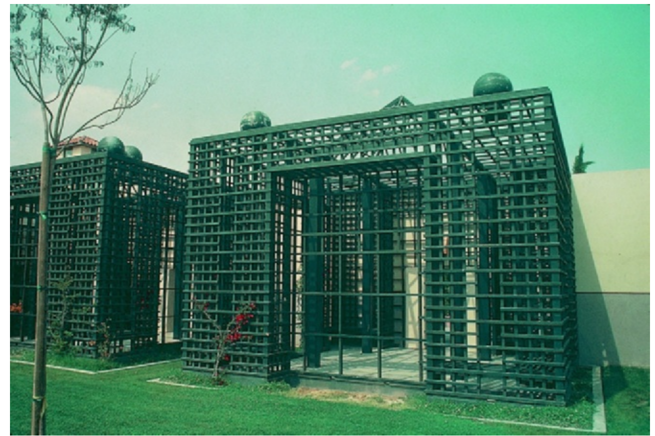


Figure 9.16f These trellised outdoor reading areas are part of the public library in San Juan Capistrano, California, designed by Michael Graves. Often a trellis is used to support vines or other climbing plants.



Figure 9.16g This pergola was designed so that most of the shade comes from the vine that it supports.

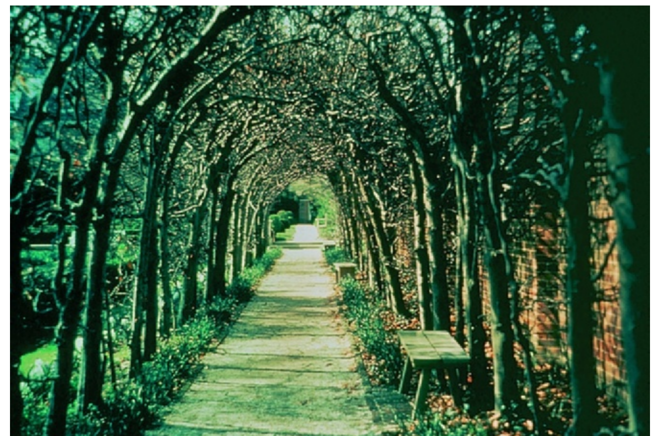


Figure 9.16h This arbor is located in the garden of the Governor's Palace, Colonial Williamsburg, Virginia. (Courtesy of Richard Kenworthy.)

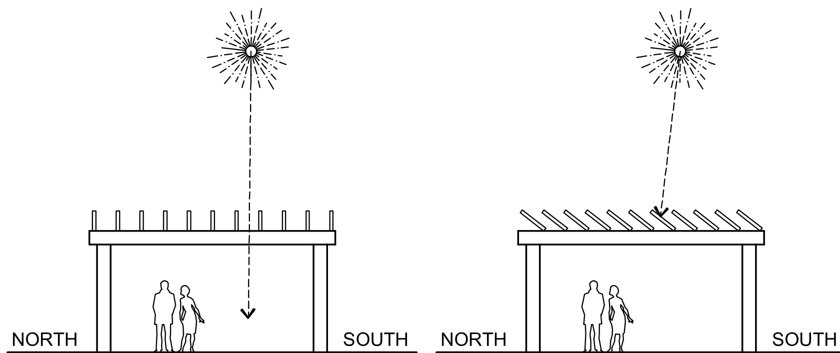


Figure 9.16i The typical pergola has shading elements that are on edge like joists. Such a design will provide little shade at 12 noon. Instead, the louvers should be tilted toward the north.



Figure 9.16j Cities can be made much more attractive by providing shade to public spaces as in this downtown park in Phoenix, Arizona.



Figure 9.16k An important element of the revitalization of an old part of Singapore, called Clarke Quay, included shading the streets to make them pedestrian friendly. The parasol-like canopies called "Angels" have an 80 percent shading coefficient produced by the combination of the ETFE (ethylene tetrafluroethylene) foil cushions and a decorative aluminum frit. The Angels are high enough to allow air to flow underneath, preventing a buildup of hot air. Of course the canopies also protect against rain.



Figure 9.16l Antione Predock used a trellis of steel bars to shade outdoor walkways and sculpture gardens at the Nelson Fine Arts Center at Arizona State University in Tempe.



Figure 9.16m Fixed, outdoor shading systems should allow hot air to escape and winter sun to enter, as in this structure in San Jose, California.

9.17 USING PHYSICAL MODELS FOR SHADING DESIGN

Heliodons were introduced earlier, and the author suggested that building or buying a heliodon is an excellent investment for an architectural office or school. Appendix I gives detailed instructions for making and using a heliodon. One of its main applications is the design of shading devices. Testing a model of a shading device not only gives feedback on the performance of the device but also teaches the designer much about the whole question of sun shading. Since this method of design is conceptually simple, it is easy to learn and remember.

Although computers are powerful and useful tools, experience has shown that an introduction to shading is still best achieved with a heliodon. The author believes that once the basic concepts are understood, the computer becomes a much more useful tool.

The step-by-step procedure for designing shading devices by means of physical models is followed by an illustrative example.

Basic Procedure for Shading Design by Means of Physical Models

1. Build a scale model of the building, a typical portion of the building facade, or a typical window.
2. Set up the heliodon and adjust it for the correct latitude (see Appendix I).
3. Place the model on the center of the heliodon tilt table. Be sure to orient the model properly (e.g., a south window should face south, as shown in Fig. 9.17a).
4. Determine the last days of the over- and underheated periods from Tables 9.5B and 9.5C for internally and envelope-dominated buildings, respectively.
5. Move the heliodon light vertically to match the date of the last day of the overheated period, check the shading on the model, and adjust the overhang as necessary.
6. Rotate the model stand to simulate the changing shadows at different hours on that date.
7. Make more adjustments, if necessary, on the model to achieve the desired shading.
8. Move the heliodon light vertically to match the date of the last day of the underheated period (winter), and check the sun penetration.
9. Make changes on the model if the sun penetration is not sufficient.

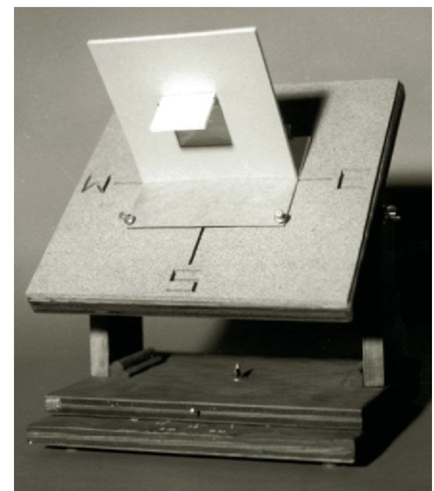


Figure 9.17a A model of a south window is placed facing south on the tilt table of the heliodon. Note that the overhang fully shades the window at 12 noon at the end of the overheated period (September 15) for this design.

10. Rotate the model stand to simulate the changing shadows for various hours on this date.
11. Repeat steps 5 to 10 until an acceptable design has been developed.

Illustrative Example

Problem

A horizontal overhang is required for a small office building (envelope-dominated) in Indianapolis, Indiana. Daylighting will not be considered in this example. The overhang is for a 5 ft wide (1.5 m) and 4 ft high (1.2 m) window on a wall facing south.

Solution

1. Build a model of the window with some of the surrounding wall. For convenience, the model should be about 6 in. (15 cm) on a side (Fig. 9.17a). Use a clear plastic film, such as acetate, for the glazing.
2. Appendix I explains how to set up and use the heliodon. Adjust the tilt table for the latitude of Indianapolis, which is 40° N latitude.
3. With pushpins or double-stick tape, tack the model to the center of the tilt table and orient it south (Fig. 9.17a).
4. From Figure 5.5, determine that Indianapolis is in climate region 3. Since it is given that the building is envelope-dominated, use Table 9.5C to determine that the last day of the overheated period is about September 15 and the last day of the underheated period is about May 7.
5. Move the heliodon light vertically to correspond with September 15. Cut and attach an overhang of such length that the shadow just reaches the windowsill (Fig. 9.17a).
6. When one rotates the model stand, the shadows for different times of the day can be investigated. Note how the sun outflanks the window before and after noon because the overhang was not wide enough (Fig. 9.17b).
7. The overhang is extended on each side of the window (Fig. 9.17c).
8. Move the lamp to the position corresponding to the last day of the underheated period, which we determined above to be about May 7. At this time, the window should still be in sun and not shaded (Fig. 9.17d). Since a shorter overhang would decrease the summer shading, use a movable overhang instead.
9. Swing the overhang up until the window is fully exposed to the winter sun (Fig. 9.17e).
10. Rotate the model stand to see how shade changes during different hours of the day.
11. The solution in this case is for an overhang that is moved twice a year. During the summer, the overhang is as shown in Figure 9.17d, and during the winter it is up, as in Figure 9.17e.

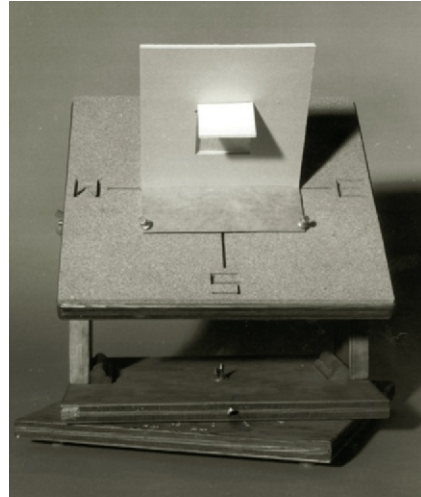


Figure 9.17b The heliodon now simulates 4 P.M. on September 15. Note how the sun is outflanking the overhang.

Model testing can reveal many surprises. For example, little sun penetrates the glazing at acute sun angles. The glazing acts almost like a mirror at these angles (Fig. 9.17f). This phenomenon is explained later in this chapter.

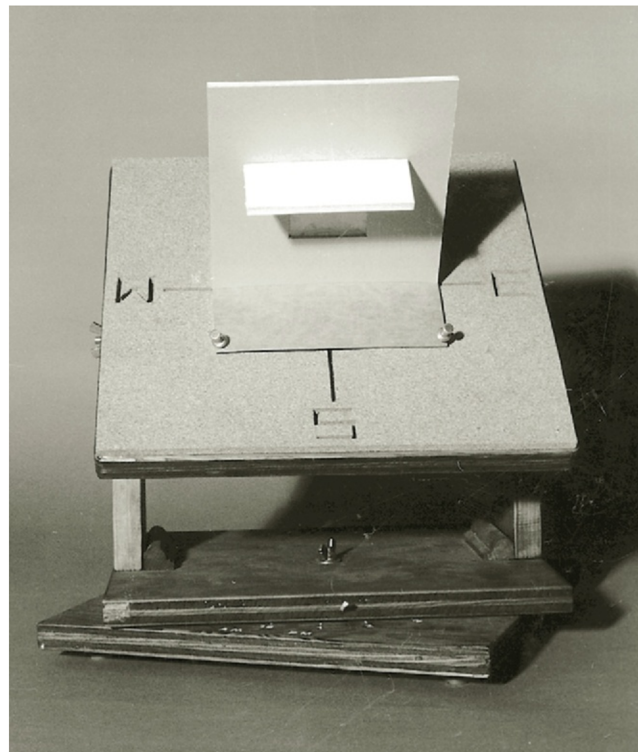


Figure 9.17c The overhang is redesigned by making it wider.

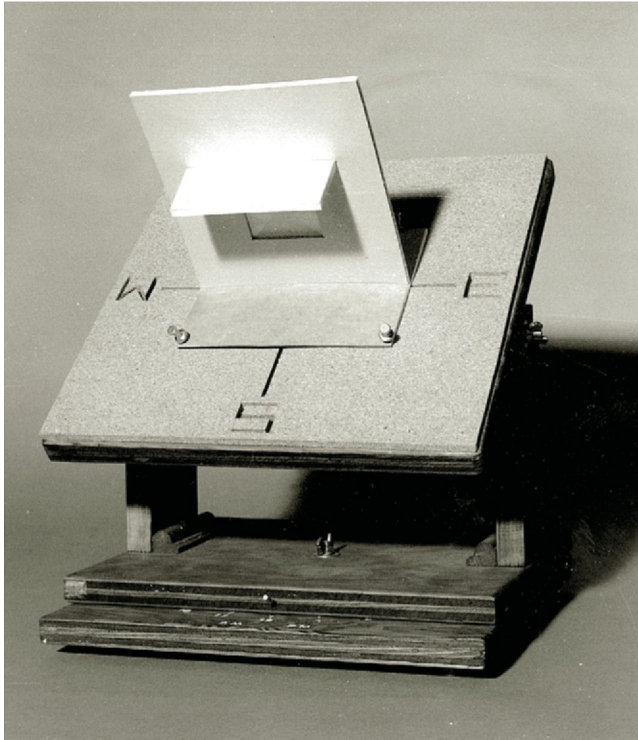


Figure 9.17d The heliodon light is readjusted to simulate the shading for the last day of the underheated period (May 7 in this case), at which time sun is still desired. Instead, the window is in shade.

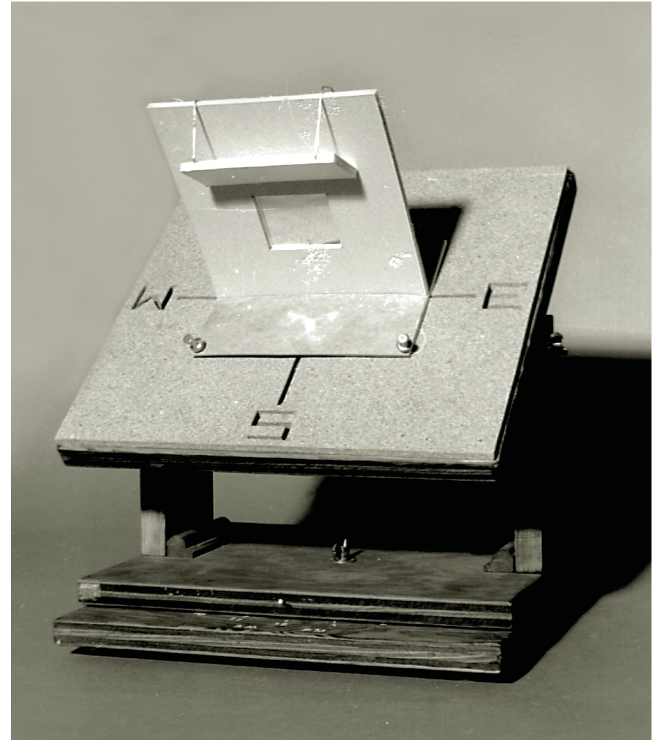


Figure 9.17e The overhang is rotated up until the window is fully exposed to the winter sun. This determines the position for the overhang during the whole underheated period.



Figure 9.17f The model shows that at very large angles of incidence (i.e. glancing angles) the sun is mostly reflected off the glazing. Note the long shadow of the pushpin and the reflections onto the ground below the window.



Figure 9.17g No matter how complicated the shading problem is, physical modeling can help the designer. Reflections from a pool are also simulated. Also note the sundial, which can be used as an alternative method to test models (see Appendix I).

Even complicated shading problems are easy to solve by physical modeling. For example, the analysis of a shading system for a complex building with odd angles and round features (Fig. 9.17g) is no more difficult than the analysis for a conventional building. Figure I.4g in Appendix I also shows how a sundial can be used with a heliodon to test models. See Appendix I, Section I.4, for an explanation of this alternate method of testing models.

Since heliodons can also easily simulate the shading from trees, neighboring buildings, and landforms, their use is also very appropriate for site planning and landscape architecture (Chapter 11).

9.18 GLAZING AS THE SHADING ELEMENT

Even the clearest and thinnest glass does not transmit 100 percent of the incident solar radiation. The radiation that is not transmitted is either absorbed or reflected off the surface (Figs. 9.18a–d). The amount that is absorbed depends on the type of, additives to, and thickness of the glazing. The amount that is reflected depends on the nature of the surface and the angle of incidence of the radiation. Each of these factors will be explained below, starting with absorption.

Absorption is mainly a function of additives that give the glazing a tint or shade of gray. Although tinted glazing reduces the light transmission, it usually does not decrease the heat gain by much because much of the absorbed radiation is then reradiated indoors (Fig. 9.18b). One type of tinted glazing is called heat absorbing because it absorbs the short-wave infrared part of solar radiation more than the visible part. But even this type of glazing reduces the solar heat gain by only a small amount.

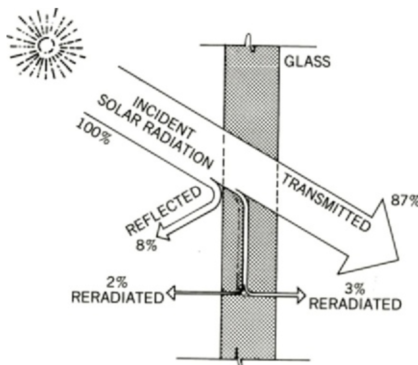


Figure 9.18a The total heat gain from the incident solar radiation consists of both the transmitted and reradiated components. For clear glazing, about 90 percent of the incident solar radiation ends up as heat gain.

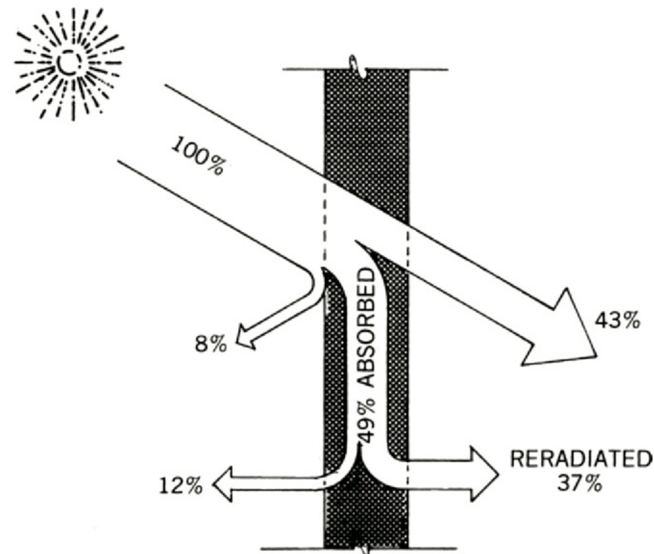


Figure 9.18b Since with tinted or heat-absorbing glass a large proportion of the absorbed solar radiation is reradiated indoors, the total heat gain is quite high (80 percent in this example).

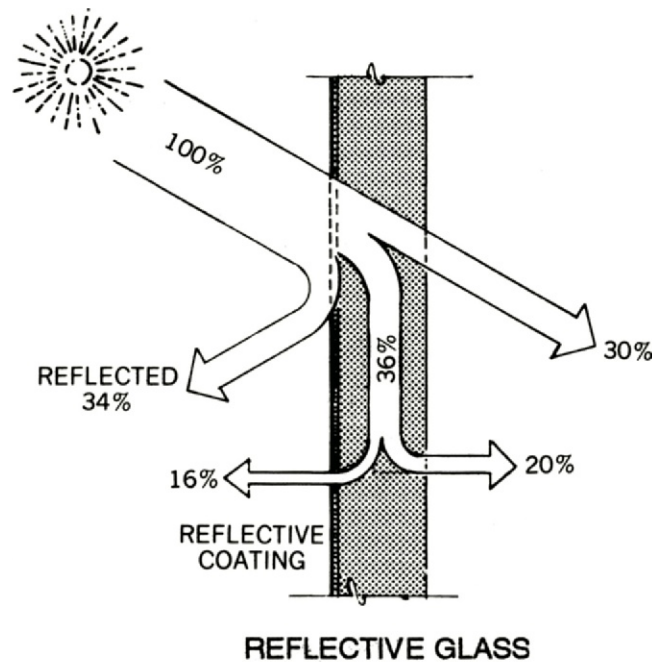


Figure 9.18c Reflective glazing effectively blocks solar radiation without color distortion. Reflective glass is available in a variety of reflectances (50 percent in this example).

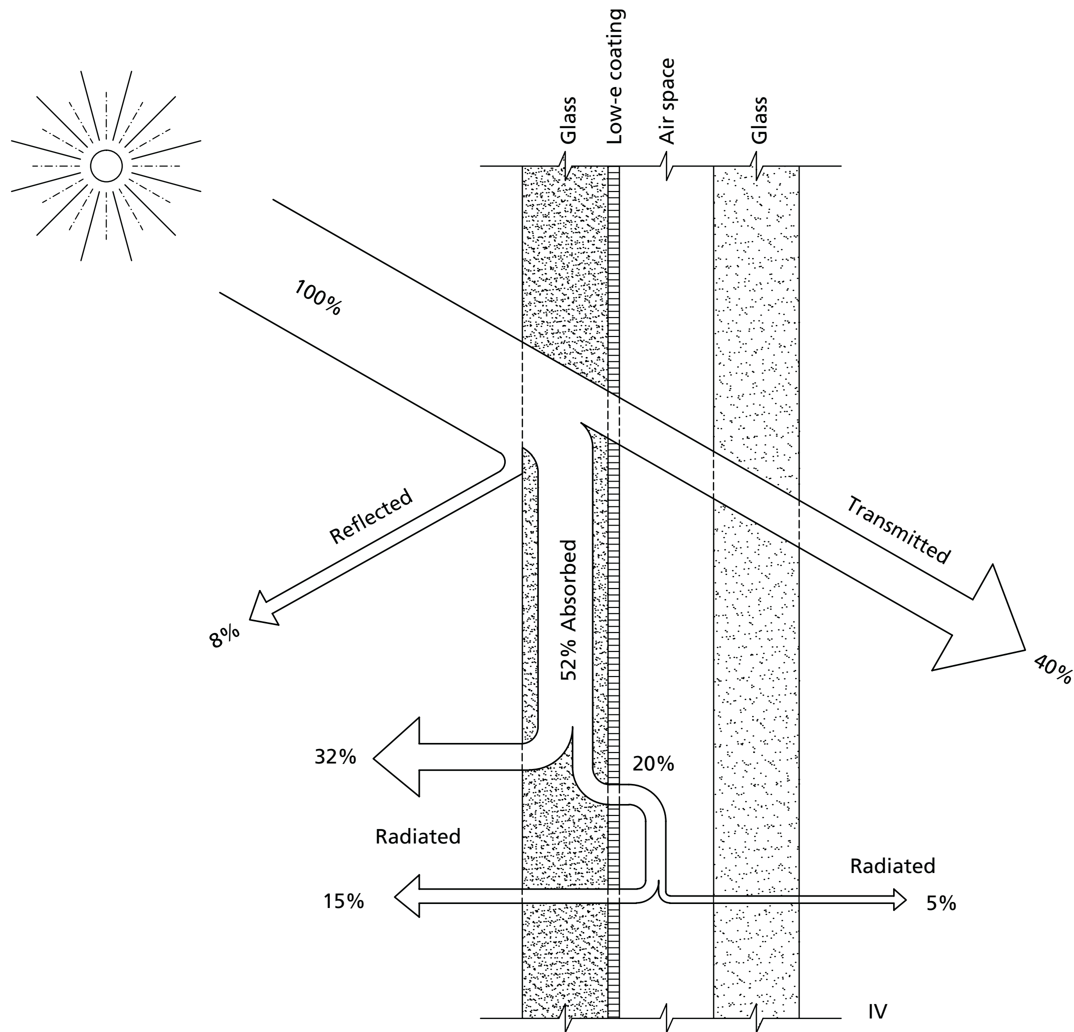


Figure 9.18d Selective low-e glazing blocks solar heat more than solar light. The combination of a low-e coating and heat-absorbing outer pane blocks most of the solar infrared and only part of the light. The transmission can be much less than the 45 percent (40 percent + 5 percent) shown by using an outer pane that absorbs more light.

Tinted glass was very popular in the 1960s because it reduced, even if only slightly, the solar load through glass-curtain walls. It also provided color to what was otherwise often stark architecture. It was originally available only in greens, grays, and browns, but recently it has also become available in blue and its popularity is again on the rise.

Glazing also blocks solar radiation by reflection. The graph in Figure 9.18e shows how transmittance is a function of the angle of incidence. It also shows how the angle of incidence is always measured from the

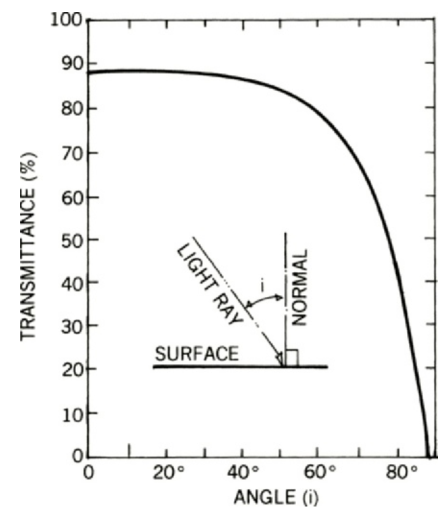


Figure 9.18e The transmittance of solar radiation through glazing is a function of the angle of incidence, which is always measured from the normal to the surface. Maximum transmission occurs when the light is perpendicular to the glass (angle i = 0), and transmission is zero when the light is almost parallel to the glass (angle > 87°).

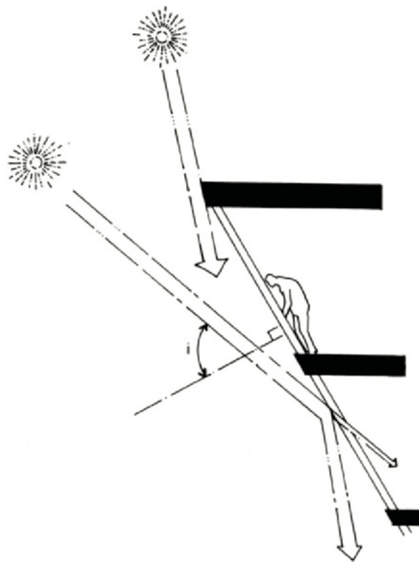




Figure 9.18f The city hall of Tempe, Arizona, is an inverted pyramid as a consequence of a shading concept. When the sun is high in the sky, the building shades itself. At low sun angles, much of the solar radiation is reflected off the glazing because of the very large angle of incidence.

normal to the surface. Notice that the transmittance is almost constant for an angle of incidence from 0° to about 45°. Above 70°, however, there is a pronounced reduction in the transmittance of solar radiation through glazing. Several architects have used this phenomenon as a shading strategy. One of the most dramatic examples is the Tempe, Arizona, city hall (Fig. 9.18f).

The angle at which sunlight strikes a window has much more impact on how much sunlight is transmitted than is generally realized. Figure 9.18g clearly shows how large angles of incidence result in reduced solar transmittance. For example, at an 80° angle of incidence (i.e., 10° from the glass), 60 percent of the solar radiation is reflected. Furthermore, the solar heating impact of the angle of incidence is also a function of the cosine law (Fig. 9.18h). The sun only sees the window in full size when it is looking at it perpendicularly. At all other angles, the sun sees a foreshortened rectangle. As a result of these two phenomena, the most solar heating of west windows is not when the solar radiation is strongest around noon but later in the afternoon around 4 P.M. (Fig. 9.18i). Consequently, it is much more

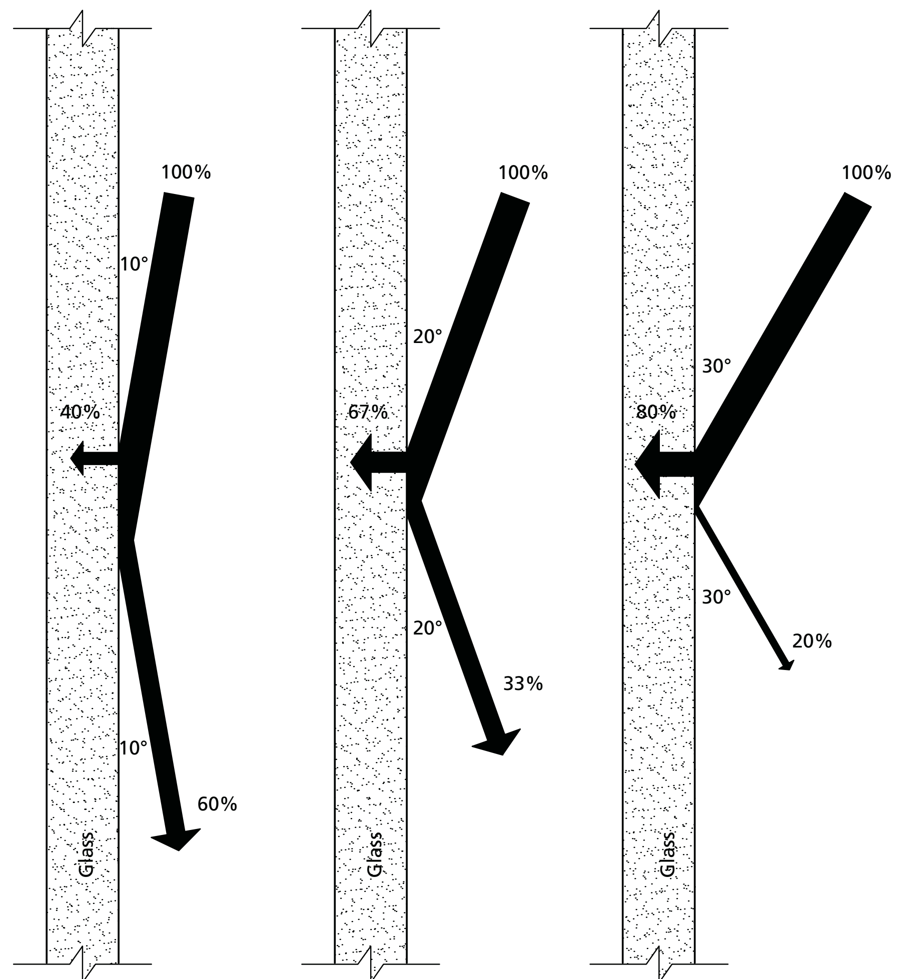


Figure 9.18g At very large angles of incidence (i.e., glancing), most light is reflected off the surface.

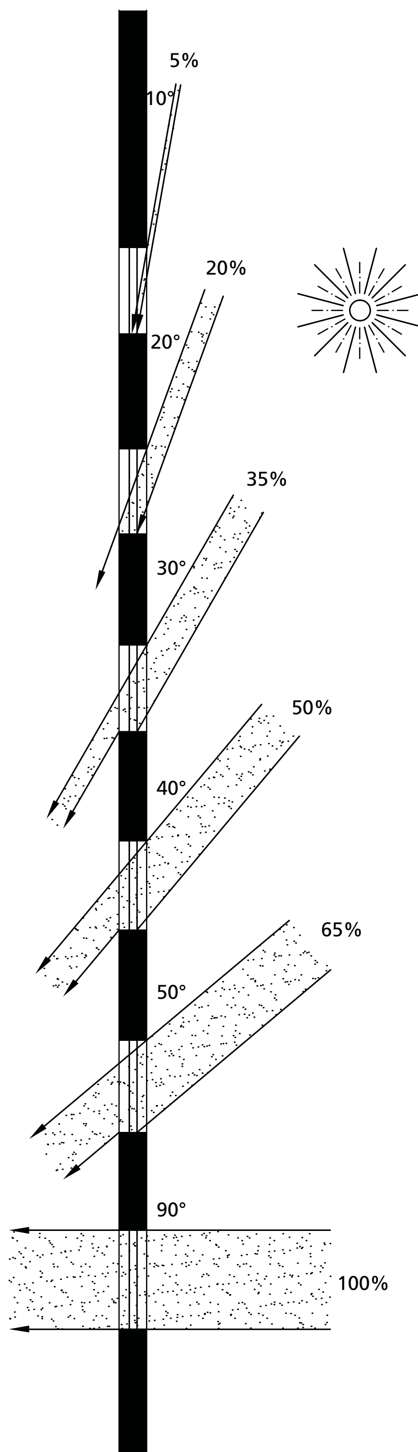


Figure 9.18h The sun only sees the full size of a window when the sunrays are perpendicular to the glazing. At all other angles, the sun sees a foreshortened window whose size is described by the cosine law. Because of the combination of this and the reflection phenomenon, short overhangs provide almost no additional benefit.

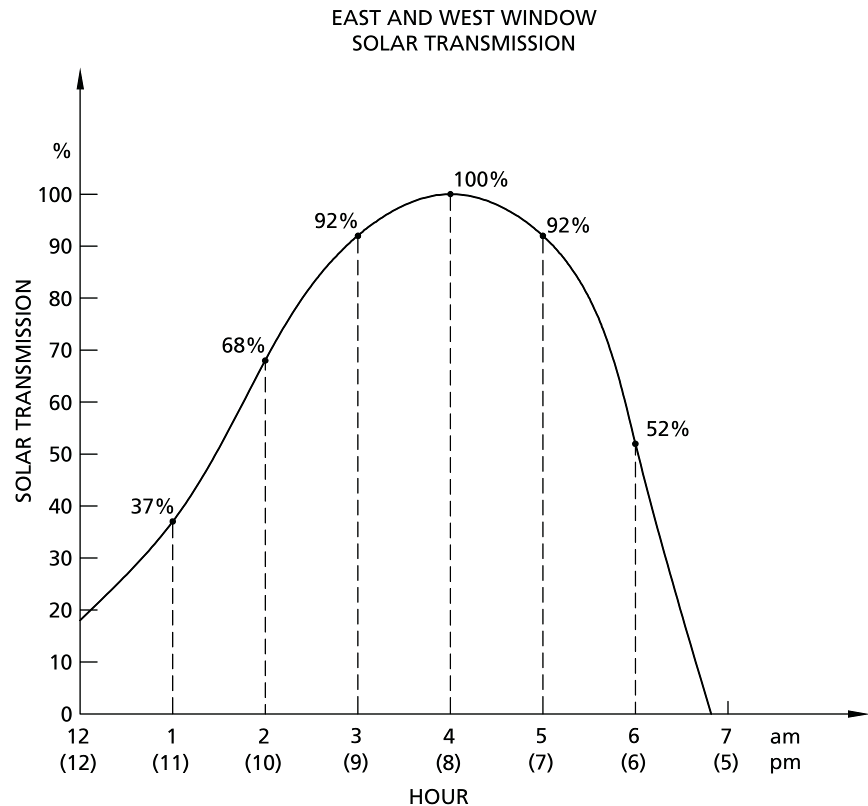


Figure 9.18i The maximum solar gain through a west window occurs at about 4 P.M. (8 A.M. for an east window). Although the sun is strongest at 12 noon, the solar gain is reduced for several hours by the cosine law and reflections off the surface of the glazing. Consequently, shading of west windows is most critical from 2 to 6 P.M. (6 to 10 A.M. for east windows).

important to shade the 4 P.M. sun than the 1 P.M. sun, which makes short overhangs mostly useless. Of course, the same is true for east and south windows. The incident angle phenomenon renders short overhangs pointless because little sun would enter the windows even if the overhangs were omitted.

The amount of solar radiation that is reflected from glazing can be increased significantly by adding a reflective coating. One surface of the glazing is covered with a metallic coating thin enough that some solar radiation still penetrates. The percentage reflectance depends on the thickness of this coating, and a mirror is nothing more than a coating that is thick enough so that no light is transmitted. Reflective glazing can be extremely effective in blocking solar radiation while still allowing a view (Fig. 9.18c). It is most appropriate on the east- and west-facing windows and south windows where winter heat is not required.

When reflective glazing became available in the 1970s, it quickly became popular for several reasons. It blocked solar radiation better than heat-absorbing glass, and did it without any color distortion. It did, however, greatly reduce the amount of light entering the windows. Reflective glazing also mirrored dramatic images of other buildings, trees, clouds, etc. Unfortunately, because it also reflects sunlight almost as much as a mirror, neighbors can end up with unexpected glare and additional solar heating. This problem arises with all types of glazing, especially at glancing angles. Consequently, all or mostly glass facades are unneighborly and should not be used (Fig. 9.18j).

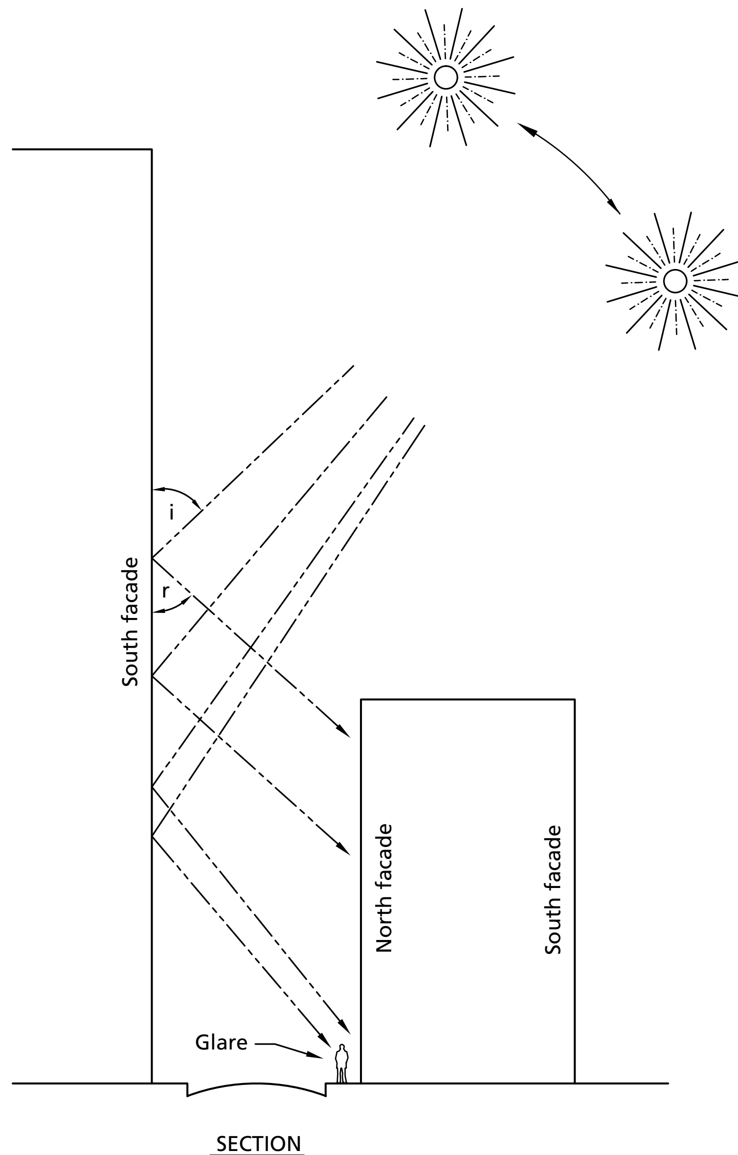


Figure 9.18j All-glass buildings are not sustainable for many reasons, including the fact that they reflect much sunlight onto other buildings and the streets below. Instead, the radiation not used for daylighting should be reflected back into space by the facade.

A building with exterior shading devices does not cause glare or reflect undesirable sunlight onto neighbors (Fig. 9.18k). Note that light entering windows from below will reflect off the ceiling creating high-quality daylight.

A much better glazing option is now available for reducing solar heat gain than either tinted or reflective glazing, and it is called **selective low-e glazing** (Fig. 9.18d). The low-e coating blocks the short-wave (solar) infrared radiation more than light radiation thereby providing "cool daylight." Because double glazing is now standard and the low-e coating is placed on the indoor side of the outdoor pane, heat-absorbing glazing can be used on the outdoor pane without much of the absorbed heat entering the building. The combination of a low-e coating and heat-absorbing glazing creates a very low solar heat gain glazing while still allowing a fair amount of light to enter.

Although tinted, reflective, and selective low-e glazing systems can be effective shading devices, they are very undiscerning. They do not differentiate between light from the sun and light from the view. They filter out light whether daylighting is desired or not. They shade equally on cloudy days and sunny days. And they block the desirable winter sun as much as the undesirable summer sun. Thus, tinted or reflective glazings are not appropriate where daylighting is desired, and neither they nor selective low-e glazing are appropriate where solar heating is desired.

When the glazing is expected to do all the shading, it has to be of a very low transmittance type. The view through this kind of glazing can make even the sunniest day look dark and gloomy. Thus, external shading devices such as overhangs not only shade best but also discern between blocking the sun and the view. Selective low-e glazing is appropriate, however, for blocking diffuse sky radiation, the low sun where no other shading would allow a view, and for glare control, which will be discussed in Chapter 13.

The directionally selective control possible with external shading can also be achieved by the glazing itself in certain special circumstances. The opaque mortar joints in glass-block construction can act as an eggcrate shading system. Also a new type of glass incorporates photoetched slats that can be ordered at any preset angle. The resultant effect will be similar to the horizontal louvers illustrated in Fig. 9.3g.

When daylighting is desired and solar heating is not, having the visible component of solar radiation pass through while heat radiation is blocked would be advantageous. Certain spectrally selective glazing systems can do that to a limited extent. Curve 3 of Figure 13.12c illustrates spectrally selective low-e glazing, which transmits cooler daylight than other glazing materials because it transmits a much higher ratio of visible-to-infrared radiation.

Much research and development work is being done on dynamic glazing systems. These are known as responsive glazing systems because they change in response to light, heat, or electricity. The sunglasses that darken when exposed to sunlight are an example of this type of glass.

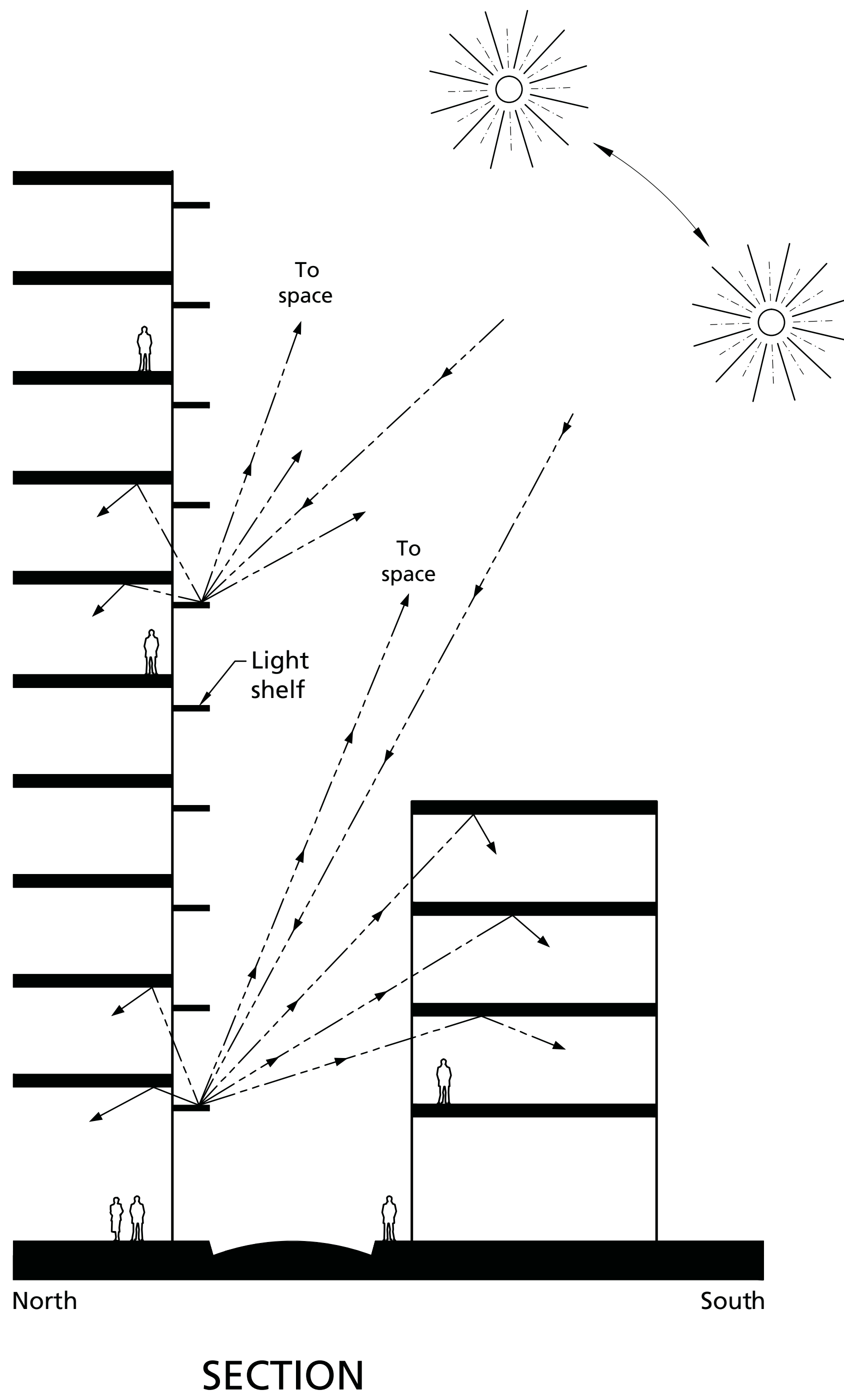


Figure 9.18k Exterior light-colored shading devices and light shelves (see Section 13.11) reflect light into outer space or up into neighboring buildings, which is desirable for daylighting purposes.

Responsive glazing can be either passive or active. Passive glazing responds directly to environmental conditions, such as light level or temperature (photochromics or thermochromics, respectively). The active system can be controlled as needed and can include such devices as liquid crystal, dispersed particle, and electrochromics.

Photochromics: These materials change their transparency in response to light intensity. They are ideal for automatically controlling the quantity of daylight allowed into a building. The goal is to let in just enough light to eliminate the need for electric lighting, but not so much that the cooling load would increase.

Thermochromics: These materials change transparency in response to temperature. They are transparent when cold and reflective white when hot. They can be used in skylights, where the loss of transparency on a hot day is not a problem, as it would be in a view window. These materials could also be used to prevent passive solar heating systems from overheating in the summer.

Liquid-Crystal Glazing: When electric charge is applied, the transparent liquid crystals align and become translucent. Thus, liquid-crystal glazing has little application for shading, but its real potential is in privacy control.

Dispersed-Particle Glazing: Although similar to liquid-crystal glazing, this material is more promising for solar control because the applied electric charge can change the transmittance of the material in a range between clear and dark states, thereby preserving the view as much as possible.

Electrochromic Glazing: This is the most promising material for shading because it can change transparency (i.e., not translucence) continuously over a wide range (about 10 to 70 percent) and can be easily controlled with an electric charge. Consequently, either a computer, a photocell, a thermostat, or the occupant can adjust the transparency as the local conditions require. This type of glazing is being used on the west windows of the Research Support Facility building of the National Renewable Energy Laboratory (NREL) at Golden, Colorado, because the great views of the mountains argued for large west-facing windows.

Rules for Glazing Selection

1. Shading with glazing should be an auxiliary system to the main outdoor shading of overhangs and fins.
2. Use clear glazing when winter solar heating is desired, and use a movable overhang to provide the summer shade.
3. When solar heating is not required, use selective low-e glazing, especially on the east and west facades. When daylighting is desired, use a different selective low-e glazing, which has a high light-to-solar gain ratio.
4. Single glazed tinted or heat-absorbing glazing should be avoided.

9.19 INTERIOR SHADING DEVICES

From an energy-rejection point of view, external shading devices are about four times more effective than indoor shading, and they block the view much less (see Fig. 9.2g). But for a number of practical reasons, interior devices, such as curtains, roller shades, venetian blinds, and shutters, are also important (Fig. 9.19a). Interior devices are often less expensive than external shading devices, since they do not have to resist the elements. They are also very adjustable and movable, which enables them to respond easily to changing requirements. Besides shading, these devices provide numerous other benefits, such as privacy, glare control, insulation, and interior aesthetics. At night, they also prevent the "black hole" effect created by exposed windows.

Since internal devices are usually included whether or not external devices are supplied, we should use them to our advantage. They should be used to stop the sun when it outflanks the exterior shading devices. They are also useful for those exceptionally hot days during the transition or underheated periods of the year when exterior shading is not designed to work. In the form of venetian blinds or light shelves (Fig. 9.19b), they can also produce fine daylighting.

One of the main drawbacks of interior devices is that they are not always discerning. They cannot block the sun while admitting the view, something that can be effectively done with an external overhang. Since they block the solar radiation on the inside of the glazing, much of the heat remains indoors. The side of the shade facing the glass should be white in order to reflect some of the solar radiation back out through the glass before it is converted to heat.

When indoor roller shades are used in conjunction with overhangs, the shades should move up from the windowsill instead of down from the window head (Fig. 9.19c). The lower portion of a window always needs more shade than the upper. Thus, some

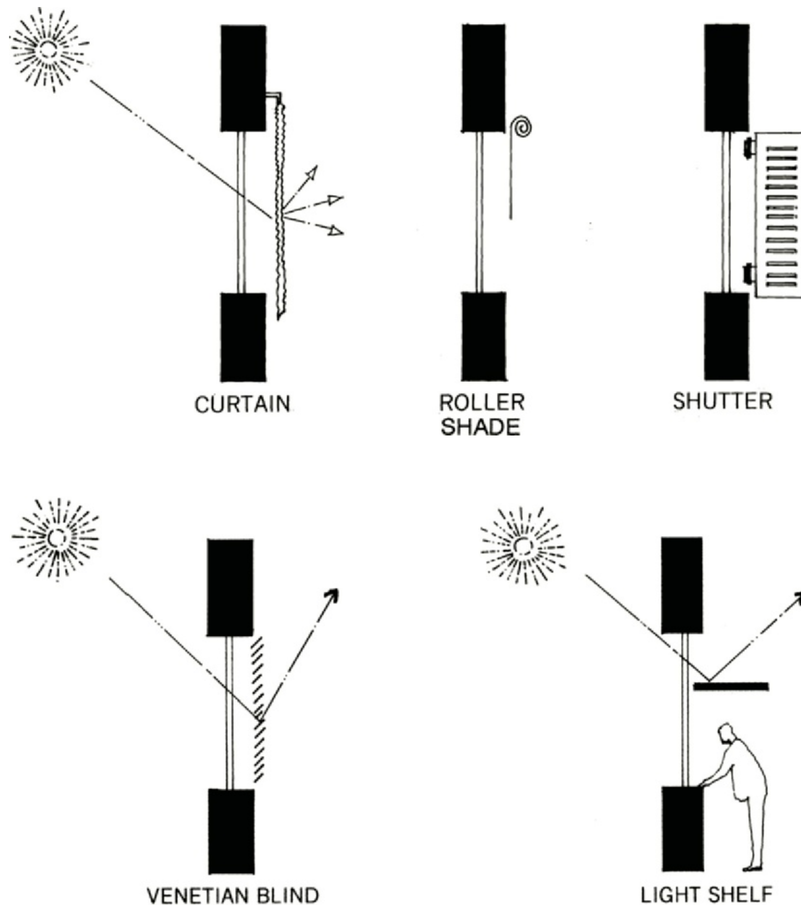


Figure 9.19a Interior shading devices for solar control.

Figure 9.19b Interior shading devices that contribute to quality daylighting.

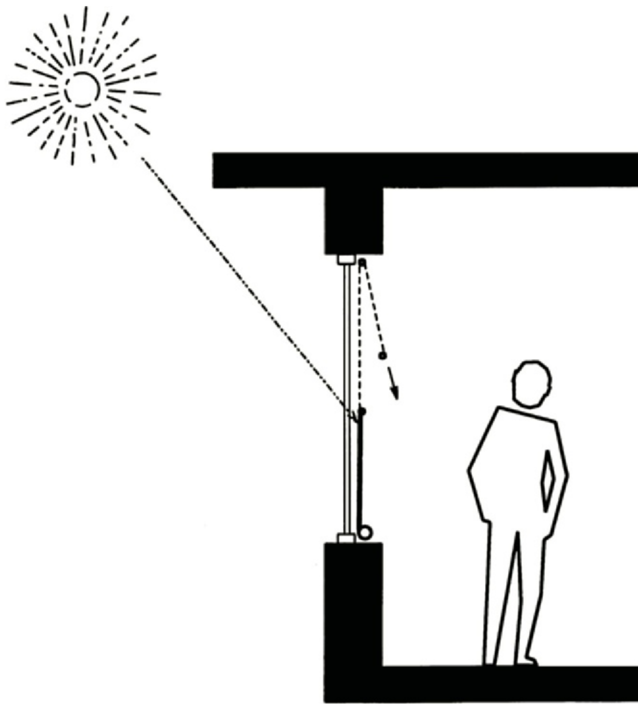


Figure 9.19c When roller shades roll up, they not only shade better but also offer better privacy.

that are about 12 inches (30 cm) apart. Since the main advantage of double skin facades is connected with natural ventilation, they are discussed in more detail in Chapter 10.

9.20 SOLAR HEAT GAIN COEFFICIENT

The performance of shading devices can be quantified by means of the **solar heat gain coefficient (SHGC)**, which can have values from 0 to 1 where 0 indicates no solar gain (complete shading) and a value of 1 indicates unimpeded solar gain (no shading). The values for common indoor shading devices such as curtains and shades can be found in Table 9.20. The table also gives values for the shading performance of various glazing systems. The SHGC is very good for describing shading

view, privacy, and daylighting can be maintained while still shading the sun.

As stated before, one of the best inventions of all time is the venetian blind. It is extremely flexible and can be used in a very directionally selective way (i.e., it can block the sun but not the view or can send the light to the ceiling for quality daylighting). Recently, venetian blinds have become even better. A new type, with tiny perforations, allows some light and view to enter even when the shades are completely closed. Although venetian blinds come in many colors, the ones with white or mirrored finishes are most functional for heating, cooling, and daylighting.

There is also a hybrid indoor/outdoor system where the shading device is located between two layers of glass. The simplest such system consists of windows where a venetian blind is placed within the double glazing. Besides a slightly better shading performance compared to indoor blinds, the venetian blind remains essentially dust free. A more elaborate hybrid system is the **double skin** facade where an outdoor venetian blind or louvers are placed between the two glass skins

Table 9.20 Shading Coefficients (SC) and Solar Heat Gain Coefficients (SHGC) for Various Shading Devices

Device	SC	SHGC
Single glazing		
Clear glass, 1/8 in (3 mm) thick	1.0	0.86
Clear glass, 1/4 in. (6 mm) thick	0.94	0.81
Heat-absorbing or tinted	0.6–0.8	0.5–0.7
Reflective	0.2–0.5	0.2–0.4
Double glazing		
Clear	0.84	0.73
Bronze	0.5–0.7	0.4–0.6
Low-e clear	0.6–0.8	0.5–0.7
Spectrally selective	0.4–0.5	0.3–0.4
Triple-clear	0.7–0.8	0.6–0.7
Glass block	0.1–0.7	
Interior shading		
Venetian blinds	0.4–0.7	
Roller shades	0.2–0.6	
Curtains	0.4–0.8	
External shading		
Eggcrate	0.1–0.3	
Horizontal overhang	0.1–0.6	
Vertical fins	0.1–0.7	
Trees	0.2–0.7	

Notes:
The smaller the number, the less solar radiation enters through a window. A value of 0 indicates that the window allows no solar radiation to enter, either directly or reradiated after being absorbed.
Ranges are given either because of the large variety of glazing types available (e.g., slightly or heavily tinted) or because of the varying geometry due to differences in orientation, sun angle, and the design of the shading device.
Source: ASHRAE Fundamentals Handbook (1997) and Egan (1975).

devices where the performance is unaffected by changes in sun angles. Unfortunately, the performance of many of the best shading devices, such as overhangs and venetian blinds, is very much affected by sun angles. Thus, the SHGC is only good in quantifying certain shading devices.

The SHGC replaced the old shading coefficient (SC), which was counterintuitive since an SC of 0 equaled complete shading while an SC of 1 equaled no shading. Since it had been widely used and is there in much of the older literature, Table 9.20 also gives the SC values to various shading devices.

Table 9.20 indicates that the best shading systems, such as horizontal overhangs, are very hard to quantify. The table shows that the SC of a horizontal overhang can vary from 0.1 (excellent) to 0.7 (poor). This is further evidence that most exterior shading devices need to be analyzed with a heliodon or a very sophisticated computer program in order to understand the potential and their effectiveness.

9.21 ROOF AND WALL REFLECTIVITY

The U.S. Environmental Protection Agency (EPA) says that for low-rise commercial buildings, the heat gain through the roof is about 50 percent of the heat gain for the entire building. This heat gain can be reduced not only by using more insulation but also by reflecting the sun's radiation. The American Society of Heating, Refrigeration, and Air-conditioning Engineers (ASHRAE) states that the heat gain through a white roof is half of that of a black roof, and the heat gain through a white wall is two-thirds that of a black wall. Thus, in hot climates, the walls should have a light color and the roof should be white.

Solar reflectivity, which is also known by the term "albedo," is a number that indicates how much of the solar radiation is reflected from a surface. An albedo of 0 indicates that no sunlight is reflected or that all sunlight is absorbed, while an albedo of 1 indicates that all sunlight is reflected. As Figure 9.21a shows, the color white has the highest solar reflectivity with an albedo of about 0.9 (90 percent is reflected) if it is fresh, clean, and glossy. Clearly then, the most sustainable buildings would have white walls and especially white roofs.

Walls

Since there is no law that requires every exterior wall to have the same color, a building could have a white east and west wall to reflect the summer sun, a dark but shaded south wall to increase winter solar gain, and a north wall of any color desired. However, in very hot climates, the south and north walls should also be light in color. Specifying walls to be

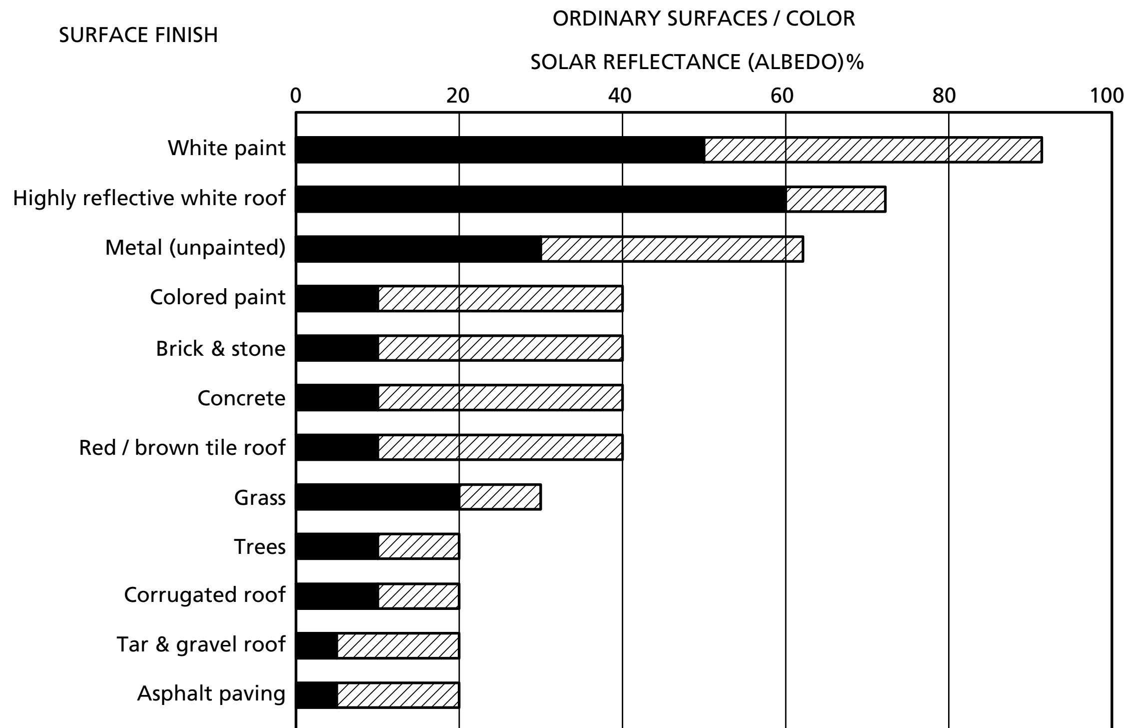


Figure 9.21a The solar reflectance, also known as albedo, is given as a range for common surfaces. For example, the solar reflection of a white surface can vary from 50 percent to about 92 percent, because of the whiteness of the base color, roughness of the surface, its age, and the degree of dirtiness. The higher end of the range represents a very clean, smooth (glossy), and fresh high reflectance white surface.

white or a very light color rarely adds to the cost of a building since these colors are standard in most building products. Two exceptions are the creation of white concrete and white brick walls. White concrete can be created by using a white cement mix or by painting with a white cement wash or paint. A white brick wall can be created by using white clay bricks, bricks with a white glaze or fired coating, or white cement wash or paint.

Glossy white surfaces reflect light much like glazing with the angles of incidence and reflection being equal, while rough white surfaces send light in all directions. To reduce the heat island effect of cities in hot climates, as much radiation as possible should be reflected back into space. To increase the amount of radiation returned to space, the wall surfaces could be jagged, as shown in Figure 9.21b.

In dark urban canyons, white walls also increase the light level on the ground both during the day and at night. White exterior walls can also help with daylighting interior spaces.

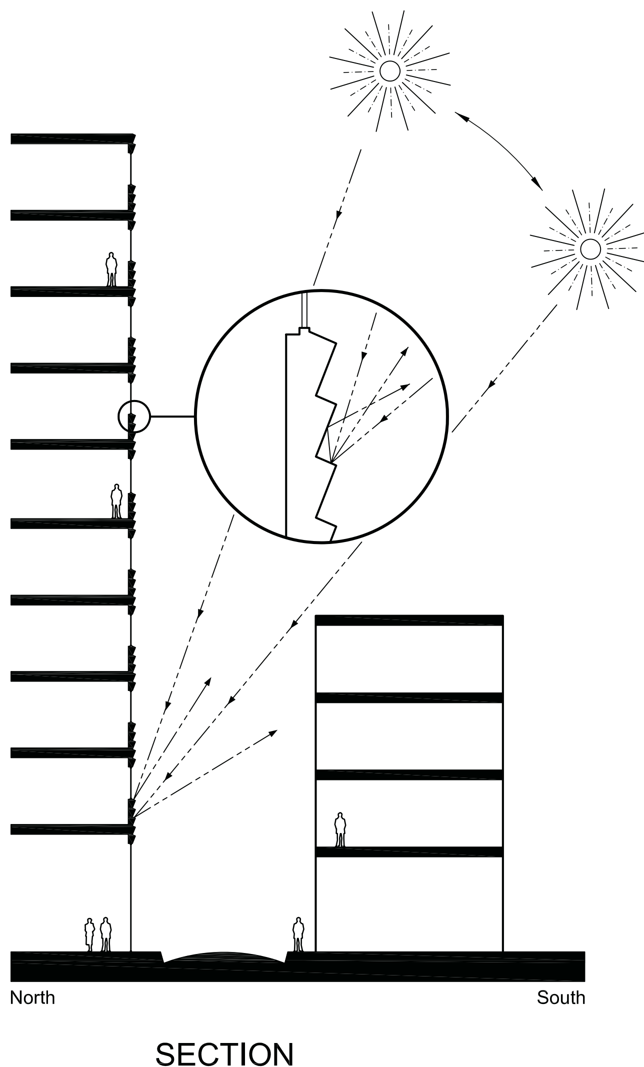


Figure 9.21b Especially in urban areas, as much sunlight as possible should be reflected back into space. Normal flat white walls diffuse the light so that only a small portion is reflected up, while glossy white walls act more like glazing. By creating walls with some what horizontal surfaces, much more sunlight can be reflected up. Wall surfaces as shown can be at any scale, even microscopic.

Roofs

There is little opposition to using white membranes on flat roofs. However, there is great opposition to using white for sloped roofs. In the hot American South, black roofs are common. When the author recommends white roofs, he is almost always told that white roofs are ugly. However, when he presents the photo of a very attractive building with a white roof (Colorplate 31), that argument is abandoned and the excuse that white roofs get dirty is raised instead. Because of their smooth finish, white metal roofs shed most dirt. The reason for the popularity of black roofs in the South is a mystery, but there is one intriguing explanation.

When General William Tecumseh Sherman marched through the South toward the end of the Civil War, he ordered most buildings to be burned. In order to cause ongoing discomfort, he ordered that all rebuilt houses have black roofs. That inappropriate color has now become the desired traditional color.

Because dark-colored sloped roofs are popular in all parts of the world, the roofing industry has produced what are called "dark-colored cool roofs." Is that phrase an oxymoron?

Cool Roofs

There is a great need to have truly cool roofs because the temperatures of dark-colored roofs routinely exceeds 160°F (71°C) on sunny summer days, while flat white surfaces reach only about 135°F (57°C), and glossy white surfaces rarely exceed 120°F (48°C). (Akbati, et al., *Cooling Our Communities*, 1992.)

There are misleading claims that dark roofs can be made "cool" by means of high-tech coatings. Table 9.21 shows that although a high-tech "cool" dark bronze coating is about two and a half times more reflective than an ordinary dark bronze coating, it is still three times less reflective than an ordinary white roof. Thus, a dark bronze "cool" roof is not cool but only less hot than a regular dark

Table 9.21 Solar Reflectance (Albedo)

Surface	Solar Reflectance	
	Normal Finish	"Cool"*
White—high reflectance	85	—
White—typical	75	80
Cream-color coating	60	67
Galvanized steel	50	—
Aluminum	50	—
Weathered concrete	35	—
Light gray coating	30	50
Middle green coating	30	40
Brick red coating	25	30
Dark green coating	25	30
White asphalt shingles	20	—
Dark bronze coating	10	25
Dark asphalt shingles	10	—
Black membrane	5	—

*Available only as a special coating.

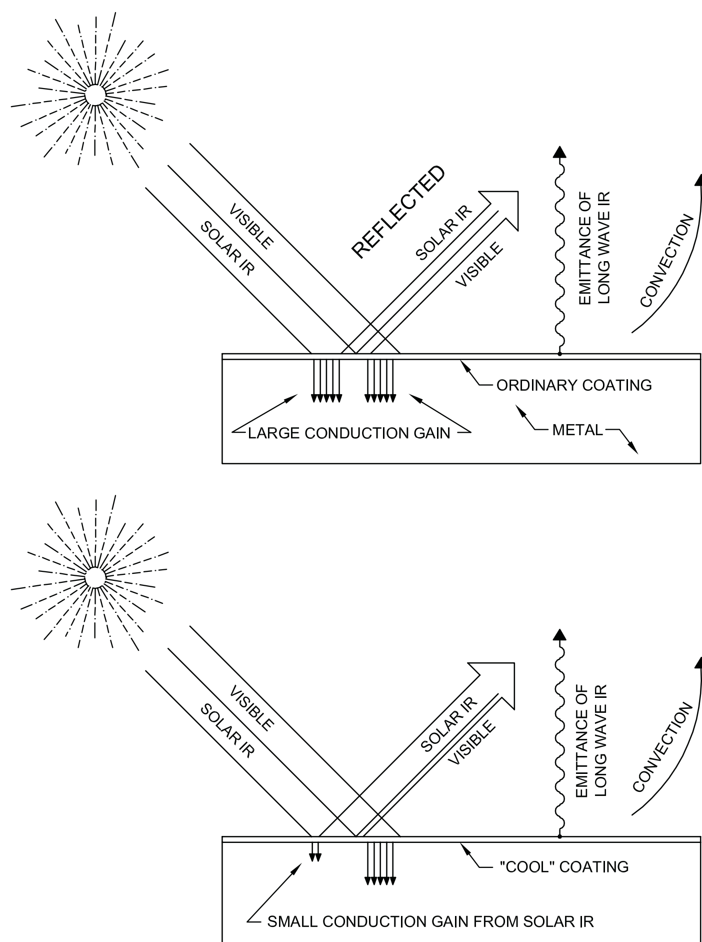


Figure 9.21c Ordinary finishes (top) reflect the short-wave (solar) infrared much like the visible part of the spectrum. However, "cool coatings" (bottom) reflect more of the solar infrared than the visible radiation.

bronze roof. For a truly cool roof, the roof surface must be as light as possible.

Usually we can predict how much the sun will heat a surface by how it appears to us (e.g., black will get much hotter than white). However, there are two exceptions to this rule. The first exception results from the technology known as "cool coatings." In normal colors, just as much solar short-wave infrared radiation is reflected as visible radiation (light), but the high-tech "cool coatings" reflect much more of the solar infrared than visible solar radiation (Fig. 9.21c). This phenomenon is most beneficial with dark colors (see again Table 9.21).

Appearances also mislead us when the surface is polished metal. Although such surfaces reflect solar radiation about as much as white colors, they are poor emitters and, therefore, get much warmer than light colors. See Section 3.11 for an explanation of this phenomenon. The **solar reflectance index** (SRI) was developed to describe the behavior of a surface in regard to not only to the solar reflectance (albedo) but also the emittance of the surface. Materials with low emittance (polished metals) will always be hotter than materials with high emittance (e.g., white paint), even when their solar reflectance might be the same.

Figure 9.21d shows how the solar reflectance (albedo) of various roof surfaces. It also shows the maximum SRI for each surface. Note that in most cases, the solar reflectance and SRI are the same for metallic surfaces because of the low emissivity of metal.

Even though white roofs are the "greenest" roofs, there is still resistance to their use because white sloped roofs are considered ugly by most people. The author believes that the dislike of white roofs is largely a result of seeing so few of them. See Colorplates 29, 31, and 33 to judge for yourself the aesthetic quality of white roofs.

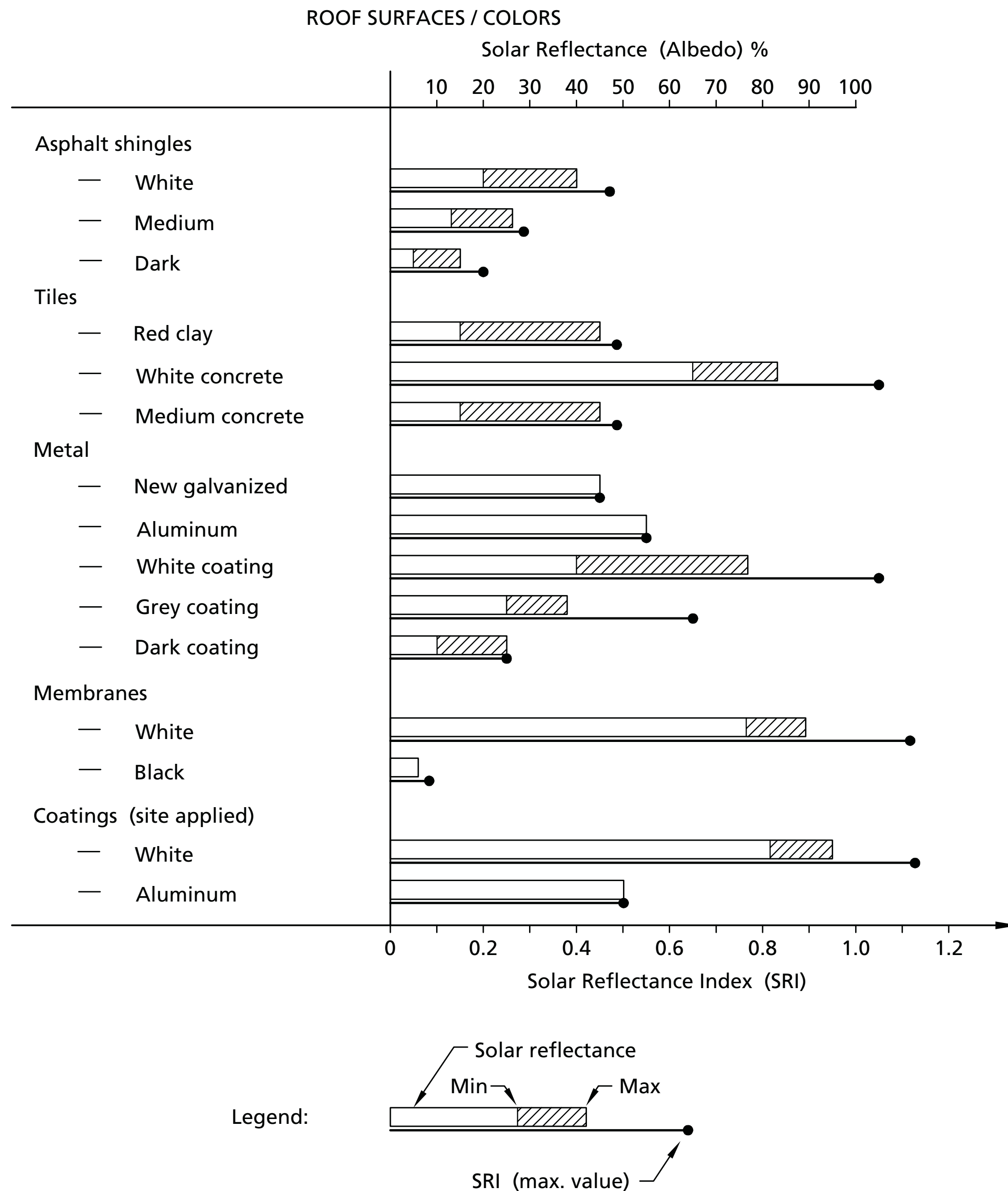


Figure 9.21d The minimum and maximum solar reflectance (albedo) values are given for various roof surfaces/colors. The maximum value is usually due to "cool roof" technology. Because the heating effect of any roof surface/color is also a function of its emissivity, the solar reflectance index (SRI) is also given. The SRI is the best indicator of what is a truly cool roof.

9.22 CONCLUSION

The ideal building from a shading point of view will have windows only on the north and south facades, with some type of horizontal overhang protecting the south-facing windows. The size and kind of overhang will depend on the type of building, climate, and latitude of the building site.

Even if there are windows on all sides, as there often will be, a building should not look the same from each direction. Each orientation faces a very different environment. James M. Fitch, in his *American Building; 2. The Environmental Forces That Shape It* (1999), pointed out that moving from the south side of a building to the north side is similar in climate change to traveling from Florida to Maine. A building can still have unity without the various facades being identical. Even the east and west facades, which are symmetrical from a solar point of view, should not always be identical. They differ because afternoon temperatures are much higher than morning temperatures and because site conditions are rarely the same (e.g., trees toward the east but not the west). One of the buildings at

the University of California at Davis exemplifies very well this unity with diversity (Figs. 9.22a and 9.22b).

If Le Corbusier had his way with the United Nations Building in New York City, our cities might have a very different appearance today. Le Corbusier wanted to use a brise-soleil to shield the exposed glazing. Not only are there no shading devices, but the building is oriented so that the glass facades face mostly east and west, while the solid stone facades face mostly north and south. Just rotating the plan could have greatly improved the performance of the building. Instead of a symbol of energy-conscious design, the building became the prototype for the glass-slab office tower that could be made habitable only by use of energy-guzzling mechanical equipment (Fig. 9.22c).

Frank Lloyd Wright also had a different image of the high-rise building. His Price Tower makes full use of shading devices (Fig. 9.22d). He, like many other great architects, realized that shading devices were central to the practice of architecture, because they not only solve an important functional problem but also make a strong aesthetic statement. This powerful potential for aesthetic expression has been largely ignored in recent years, but the energy crisis of 1973 renewed our interest in this very important and visible part of architecture (Fig. 9.22e). Global warming makes it imperative to create sustainable low-energy buildings, and such buildings must shade the sun during the overheated part of the year.



Figure 9.22a The south and east facades of the Biological Sciences Building at the University of California at Davis illustrate how unity can be maintained while each orientation responds to its unique conditions.



Figure 9.22b The north and west facades of the same building shown in Figure 9.22a. Shading requires a different response on each orientation.



Figure 9.22c The office slab of the United Nations headquarters in New York City, 1950, became the prototype for many office buildings. Le Corbusier was very upset when he discovered that the blank walls faced mostly north and south, while the glass facades faced mostly east and west and were in no way protected by sunshades.



Figure 9.22d The Price Tower, Bartlesville, Oklahoma, designed by Frank Lloyd Wright, uses sunshading as a major design concept. (Photograph by James Bradley.)

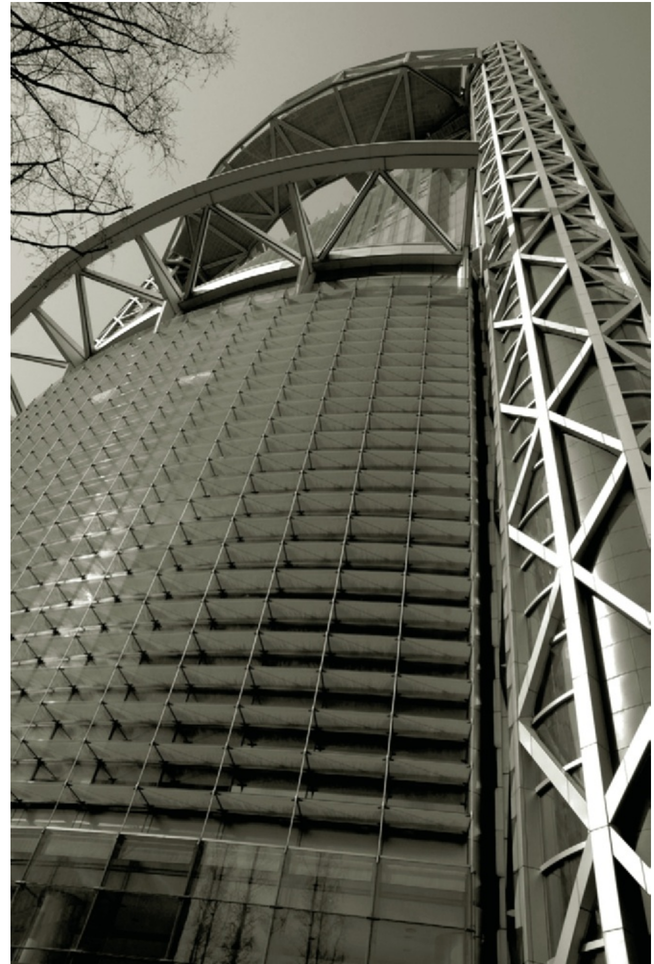


Figure 9.22e The Samsung headquarters building in Seoul, South Korea, uses green-tinted glass overhangs (louvers) to shade the windows.

KEY IDEAS OF CHAPTER 9

1. Shading is an integral part of architecture that has traditionally offered great opportunity for aesthetic expression (e.g., the Greek portico).
2. Every orientation should have a different shading strategy.
3. Maximize south glazing because it is the only orientation that not only can be effectively shaded in the summer while preserving the view but also can harvest a maximum of solar radiation in the winter.
4. Maximize north glazing in very hot climates that have no or mild winters.
5. Minimize east and west glazing because it is impossible to fully shade those orientations while maintaining the view.
6. Glazing on the east and west facades should face north or south.
7. Movable shading devices are much better than fixed devices because the thermal year and the solar year are out of phase and because of the variability of the weather.
8. Plants can be excellent shading devices. Deciduous plants can act as movable shading devices.
9. On the east and west facades, the horizontal overhang is preferred over vertical fins.
10. Movable fins are much more effective than fixed fins.
11. Eggcrate shading of small units is not recommended. However, egg-crate units the size of rooms are recommended.
12. Exterior shading is superior to both interior shading and the shading from the glazing itself.
13. Use indoor shading devices to back up the outdoor shading devices.

14. Outdoor spaces should be carefully shaded to make them attractive in the summer.
15. Light transmission through glazing is a function of the angle of incidence.
16. Use selective low-e glazing when low transmission of solar radiation is desired.
17. Since walls and especially roofs are hard to shade, use very light colors to reflect the solar radiation. In hot climates, white roofs are best. “Cool coatings” are not as cool as white coatings.
18. “Cool coatings” should be called “less hot coatings.” White is better than any “cool coating.”

References

ASHRAE. *ASHRAE Fundamentals Handbook*. Atlanta: ASHRAE.

Egan, M. D. *Concepts in Thermal Comfort*. Englewood Cliffs, NJ: Prentice Hall, rev. ed. 1999.

Fitch, J. M., with W. Bobenkausen. *American Building: 2. The Environmental Forces That Shape It*. New York: Schocken, 1999.

Resources

Further Reading

(See the Bibliography in the back of the book for full citations.)

ASHRAE. *ASHRAE Fundamentals Handbook*.

Baird, G. *The Architectural Expressions of Environmental Control Systems*.

Brown, G. Z., and M. DeKay. *Sun, Wind, and Light*, 3rd ed.

Carmody, J. et al. *Residential Windows: A Guide to New Technologies and Energy Performance*, 3rd ed.

———. et al. *Window Systems for High-Performance Buildings*.

Egan, M. D. *Concepts in Thermal Comfort*.

Fitch, J. M., with W. Bobenhausen. *American Building: 2. The Environmental Forces That Shape It*.

Franta, G., K. Anstead, and G. D. Ander. *Glazing Design Handbook for Energy Efficiency*.

Kwok, A., and W. Grondzik. *The Green Studio Handbook: Environmental Strategies for Schematic Design*, 2nd edition.

Olgyay, A., and V. Olgyay. *Solar Control and Shading Devices*.

Ramsey Sleeper Architectural Graphic Standards, 11th ed. CD-ROM version is also available.

Stein, B., J. S. Reynolds, W. T. Grondzik, and A. G. Kwok. *Mechanical and Electrical Equipment for Buildings*, 10th ed.

Sources of Shading Devices

Fixed Shading Devices

Accurate Perforating
www.accurateperforating.com

Airolite
www.airolite.com

Architectural Louvers
www.archlouvers.com

Architectural Shade Products
www.architecturalshade.com

Armetco Systems
www.armetco.com

ASCA
www.asca-design.com

AWV Solar Shading Systems
www.awv.com

Colt
www.shadinglouvers.com

C. R. Laurence Company
www.crlaurence.com

CS Construction Specialties
www.c-sgroup.com

Doralco
www.doralco.com

Eliosolar
www.eliosolar.com

Gamco Corp.
www.gamcocorp.com

Hendrick Architectural Products
www.hendrickarchproduts.com

Industrial Louvers Inc.
www.industriallouvers.com

Kawneer
www.kawneer.com

OGI Architectural Metal Solutions
www.ohiogratings.com

Pac-Clad Peterson Aluminum
www.pac-clad.com

Quality Metacrafts, LLC/Americlad
www.americlad.com

Ruskin
www.ruskin.com

Tubelite Inc.
www.tubeliteinc.com

Unicel Architectural
www.unicelarchitectural.com

Uni-Clad, Firestone
www.uniclad.com

Dynamic Shading Systems

American Warming and Ventilating
www.shadinglouvers.com

Construction Specialties
www.c-sgroup.com

Gradhermetic
www.gradhermetic.es

Hunter Douglas
www.hunterdouglascontract.com

Sefar Architecture
www.tenarafabric.com

Technal
www.technal.es

Warema
www.warema.com

Weather Guard Building Products
www.wbuildingproducts.com

Willard Shutter Co., Inc.

Fabric Shading

B&C Awnings Inc.
www.bcawnings.com

Cambridge Architectural
www.cambridgearchitectural.com

Cascade Coil Drapery
www.cascadecoil.com

Draper Inc.
www.draperinc.com

Durasol Awnings
www.durasol.com

Ferrari Textiles Corp.
www.soltis-textiles.com

Firesist
www.glenraven.com/firesist

GKD-USA
www.gkdusa.com

Rollingshield
www.rollingshield.com

Shade Fla
www.shadefla.com

Shade Tree
www.shadetreecanopies.com

TriVantage, LLC
www.trivantage.com

Shading with Plants

Greenscreen
www.greenscreen.com

Jakob Inc.
www.jakob-usa.com

CHAPTER 10

PASSIVE COOLING

Optimizing the building envelope for the climate can substantially reduce the size of the mechanical system.

ASHRA Energy Design Guide for Small to Medium Office Buildings

True regional character cannot be found through a sentimental or imitative approach by incorporating either old emblems or the newest local fashions which disappear as fast as they appear. But if you take, for instance, the basic difference imposed on architectural design by the climatic conditions of California, say, as against Massachusetts, you will realize what diversity of expression can result from this fact alone.

Walter Gropius

Scope of Total Architecture, *1955*

10.1 INTRODUCTION TO COOLING

To achieve thermal comfort in the summer in a more sustainable way, one should use the three-tier design approach (Fig. 10.1). The first tier consists of **heat avoidance**. At this level, the designer does everything possible to minimize heat gain in the building. Strategies at this level include the appropriate use of shading, orientation, color, vegetation, insulation, daylight, and the control of internal heat sources. These and other heat-avoidance strategies are described throughout this book.

Since heat avoidance is usually not sufficient by itself to keep indoor temperatures low enough all summer, the second tier strategies of **passive cooling** should also be used. With some passive cooling systems, temperatures are actually lowered and not just minimized, as is the case with heat avoidance. Passive cooling also includes the use of air motion to shift the comfort zone to higher temperatures. The major passive cooling strategies will be discussed in this chapter.

In many climates, there will be times when the combined effort of heat avoidance and passive cooling is still not sufficient to maintain thermal comfort. For this reason, the third tier of mechanical equipment is usually required. In a sustainable design process, as described here, this equipment must cool only what heat avoidance and passive cooling could not accomplish. Consequently, the mechanical equipment will be quite small and use only modest amounts of energy, thereby saving both money and the environment.

10.2 HISTORICAL AND INDIGENOUS USE OF PASSIVE COOLING

Examples are sometimes better than definitions in explaining concepts. The following examples of historical and indigenous buildings will illustrate what is meant by passive cooling.

Passive cooling is much more dependent on climate than passive heating. Thus, the passive cooling strategies for hot and dry climates are very different from those for hot and humid climates.

In hot and dry climates, one usually finds buildings with few and small windows, light surface colors, and massive construction, such as adobe, brick, or stone (Fig. 10.2a). The massive materials not only retard and delay the progress of heat through the walls, but also act as a heat sink during the day. Since hot and dry climates have high diurnal temperature ranges, the nights tend to be cool. Night ventilation can then be used to cool the indoor mass, which will then act as a heat sink the next day. To prevent the heat sink from being overwhelmed, small windows and light colors are used to minimize the heat gain. Closed shutters further reduce the daytime heat gain, while still allowing good night ventilation when they are open.

In urban settings and other places with little wind, wind scoops are sometimes used to maximize ventilation. Wind scoops were already used several thousand years ago in Egypt (Fig. 10.2b), and they are still found in the Middle East today. When there is a strong prevailing wind direction, as in Hyderabad, Pakistan, the scoops are all aimed in the same direction (Fig. 10.2c). In other areas, where there is no prevailing wind direction, such as Dubai on the Persian Gulf, wind towers with many openings are used. These rectangular towers are divided by diagonal walls, which create four separate air wells facing four different directions (Fig. 10.2d).

Wind towers have shutters to keep out unwanted ventilation. In dry climates, they also have a means of evaporating water to cool the incoming air. Some wind towers have porous jugs of water at their base, while others use fountains or trickling water (Fig. 10.2e).

The *mashrabiya* is another popular wind-catching feature in the Middle East (Fig. 10.2f). These bay windows were comfortable places

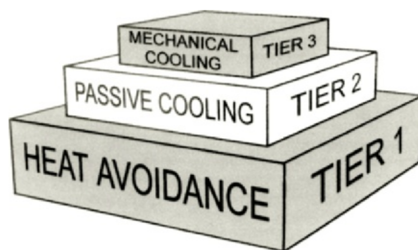


Figure 10.1 Sustainable cooling is achieved by the three-tier design approach. This chapter covers tier two.

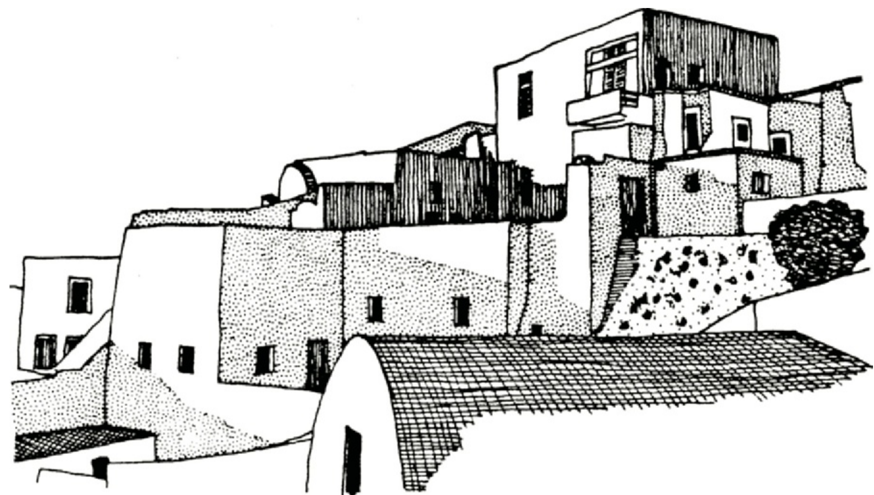


Figure 10.2a Hot and dry climates typically have buildings with small windows, light colors, and massive construction. Thera, Santorini, Greece. (From *Proceedings of the International Passive and Hybrid Cooling Conference*, Miami Beach, Florida, Nov. 6–16, © American Solar Energy Society, 1981.)

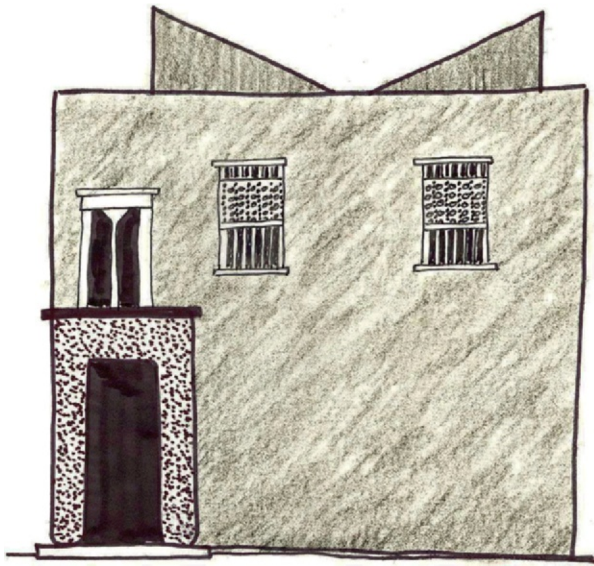


Figure 10.2b Ancient Egyptian houses used wind scoops to maximize ventilation. (After a wall painting in the Tomb of Nebamun, circa 1300 B.C., at the Metropolitan Museum of Art, New York City, #30.4.57.)



Figure 10.2d The wind towers in Dubai, United Arab Emirates, are designed to catch the wind from any direction. These substantial wind towers evolved from the one shown in Fig. 1.2d. (Photograph by Mostafa Howeedy.)

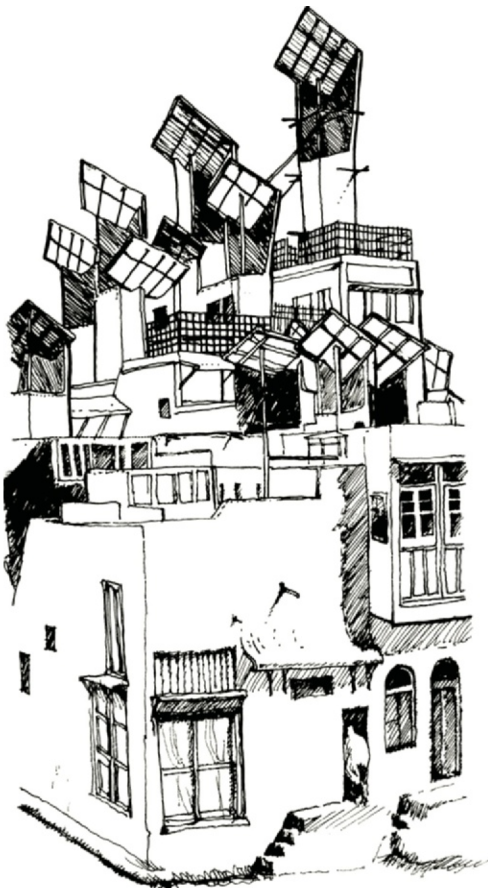


Figure 10.2c The wind towers in Hyderabad, Pakistan, all face the prevailing wind.

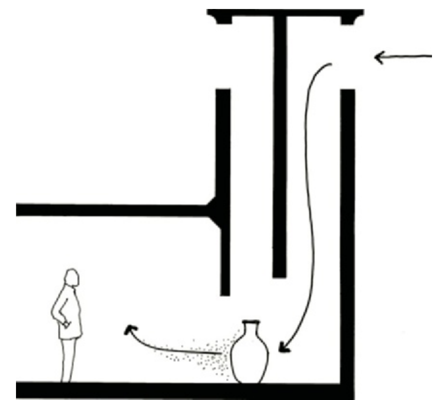


Figure 10.2e Some wind towers in hot and dry areas cool the incoming air by evaporation.



Figure 10.2f A *mashrabiya* is a screened bay window popular in the Middle East. It shades, ventilates, and provides evaporative cooling. Cairo, Egypt. (Photograph by Mostafa Howeedy.)

to sit and sleep, since the delicate wood screens kept most of the sun out yet allowed the breezes to blow through. Evaporation from porous jugs of water placed in the *mashrabiya* cooled not only drinking water but the houses as well. The *mashrabiya* also satisfied the cultural need to give women an inconspicuous place to view the activity of the outside world.

Wherever the humidity is low, evaporative cooling is very effective. Fountains, pools, water trickling down walls, and transpiration from plants can all be used for evaporative cooling. The results are best if the evaporation occurs indoors, in the incoming air stream, or in a courtyard that is the main source of air for a building (Fig. 10.2g).

Small and deep courtyards or atriums are beneficial in hot and dry climates, not only because they are self-shading most of the day but also because they block the hot wind that would blow away the cool air. This benefit is a liability in hot and humid climates, where cross ventilation is desirable.

Massive domed structures are an appropriate strategy in hot and dry regions. Besides the thermal benefit of their mass, their form yields two different benefits. During the day, the sun sees little more than the horizontal footprint of the dome, while at night almost a full hemisphere sees the night sky. Thus, radiant heating is minimized while radiant cooling is maximized. Domes also have high spaces where stratification will enable the occupants to inhabit the cooler lower levels (Fig. 10.2h). Sometimes vents are located at the top to allow the hottest air to escape. The most dramatic example of this kind of dome is the Pantheon, in Rome. Its oculus allows light to enter while the hot air escapes. The same concept was used in the U.S. Pavilion at Expo 67 in Montreal. The upper panels of the geodesic dome had round openings to vent the hot air (see Fig. 9.15a).

A large quantity of earth or rock is an effective barrier to the extreme temperatures in hot and dry climates. The deep earth is usually near the mean annual temperature of a region, which in many cases is cool enough for the soil to act as a heat sink during summer days. Earth sheltering is discussed in more detail in Chapter 15.

In Cappadocia, Turkey, thousands of dwellings and churches have been excavated from the volcanic tufa cones over the last 2000 years (Fig. 10.2i). Many of these spaces are still inhabited today, in part because they provide effective protection from extreme heat and cold.

A structure need not be completely earth-sheltered to benefit from earth-contact cooling. The dwellings abutting the cliffs at Mesa Verde, Colorado, make use of the heat-sink capacity of both the rock cliff and the massive stone walls. The overhanging, south-facing cliffs also offer much shade during summer days (Fig. 10.2j). In areas where rock was not available, thick earthen walls were used. The Navajo people of the dry Southwest built **hogans** for the insulating effect of their thick earthen walls and roofs (Fig. 10.2k). Spanish settlers used adobe for the same purpose (Fig. 10.2l).

In hot and dry climates, maximize shading and thermal mass while minimizing daytime natural ventilation!

In hot and humid climates, we find a different kind of building, one in which the emphasis is on natural



Figure 10.2g Many traditional courtyard houses have all of their windows and doors facing the courtyard in large part for thermal comfort. The courtyard stays relatively cool because it is self-shading most of the day and because it is protected from hot winds. Further comfort comes from transpiration from plants and evaporation from fountains. Marrakesh, Morocco.



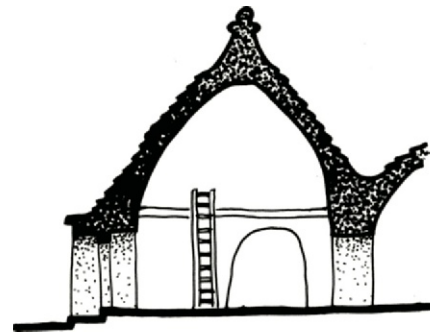


Figure 10.2h The *trulli* are conical stone houses in Apulia, Italy. Their large mass and high ceilings, with the resultant stratification of air, make these houses comfortable in summer. (From *Proceedings of the International Passive and Hybrid Cooling Conference*, Miami Beach, Florida, Nov. 6–16, © American Solar Energy Society, 1981.)

ventilation. In very humid climates, mass is a liability and very lightweight structures are best. Although the sun is not as strong as in dry climates, the humidity is so uncomfortable that any additional heating from the sun is very objectionable. Thus, in very humid regions, we find buildings with large windows, large overhangs, and low mass. Where possible the best solution was to minimize the walls (Fig. 10.2m; see also Fig. 17.2g). Sometimes buildings are set on stilts to catch more wind and to rise above the humidity near the ground. High ceilings allow the air to stratify, and vents at the gable or ridge allow the hottest air to escape (see Fig. 1.2c).

In hot and humid regions, maximize shading and natural ventilation while minimizing thermal mass!

Much of Japan has very hot and humid summers. To maximize natural ventilation, the traditional Japanese house uses post-and-beam construction, which allows the lightweight paper wall panels to be moved out of the way in the summer (Fig. 10.2n). Large overhanging roofs protect these panels and also create an outdoor space called an *engawa*. Large gable vents further increase the ventilation through the building (Fig. 10.2o).

Gulf Coast houses and their elaborate version, the French Louisiana

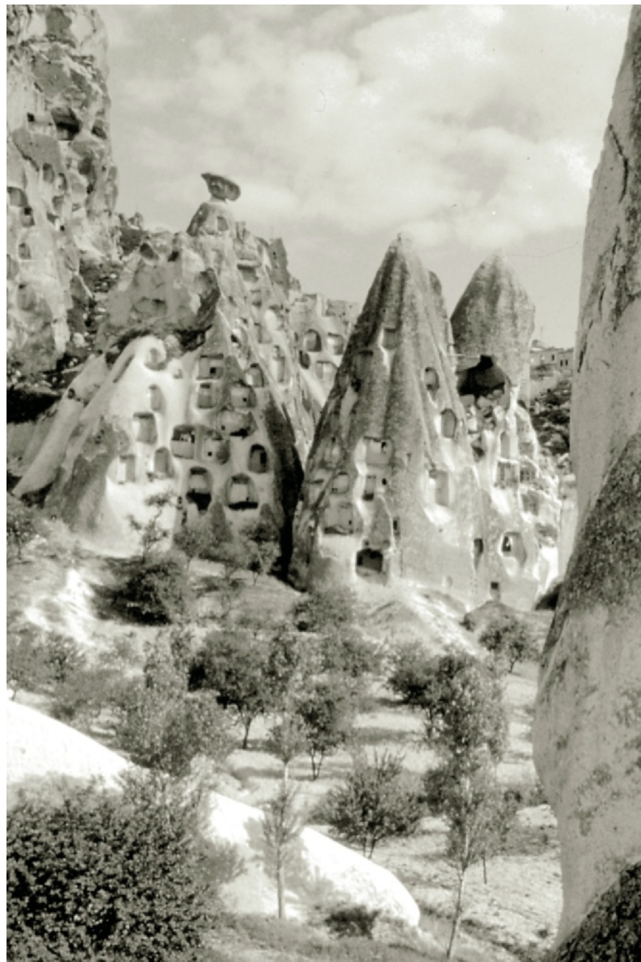


Figure 10.2i Dwellings and churches are carved from the volcanic tufa cones in Cappadocia, Turkey. (Photograph by Tarik Orgen.)

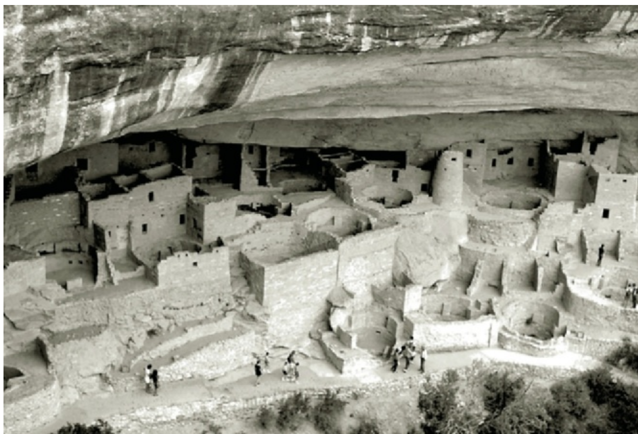


Figure 10.2j The cliff dwellings at Mesa Verde, Colorado, benefit from the heat-sink capacity of the stone walls and rock cliff.



Figure 10.2k The Navajo hogan, with its thick earthen walls, provides comfort in the hot and dry Southwest.

plantation houses, were well adapted to the very humid climate (Fig. 10.2p). In that region, a typical house had its main living space, built of a light wood frame, raised off the damp and muggy ground on a brick structure. Higher up, there was more wind and less humidity. The main living spaces had many tall openings to maximize ventilation. The ceiling was very high (sometimes as high as 14 ft [4.2 m]) to permit the air to stratify and the people to occupy the lower, cooler layers. Vents in the ceiling and high dormers with operable windows allowed the stack effect and wind to exhaust the hottest air from the building. Deep verandas shaded the walls and created cool outdoor areas.

The common open central hallway was derived from the dogtrot houses of the early pioneers of the South, who built one roof over two log cabins spaced about 10 ft (3 m) apart (Fig. 10.2q). In the summer, this shady, breezy outdoor space became a desirable hangout for dogs and people alike.

Many of these same concepts were incorporated in the Classical Revival architecture that was so popular in the South during the nineteenth century. As was mentioned in Chapter 9, the classical portico was a very suitable way to build the large overhangs needed to shade the high doors and windows. These openings were often as high as 12 ft (3.6 m), and the windows were frequently triple hung so that two-thirds of the window could be opened. Louvered shutters allowed ventilation when sun shading and privacy were desired (Fig. 10.2r). The classical image of white buildings was also very appropriate for the hot climate.



Figure 10.2l Spanish missionaries and settlers used thick adobe walls for thermal comfort.



Figure 10.2m These "chickees," built by the Indians of southern Florida, respond to the hot and humid climate by maximizing ventilation and shade while minimizing thermal mass. The diagonal poles successfully resist hurricane winds.



Figure 10.2n Ventilation is maximized by movable wall panels in traditional Japanese houses. (Courtesy of the Japan National Tourist Organization.)



Figure 10.2o The movable wall panels open onto the *engawa* (veranda), which is protected by a large overhang. Also note the large gable vent. Japanese Garden, Portland, Oregon.



Figure 10.2p This Gulf Coast house incorporated many cooling concepts appropriate for hot and humid climates. Note the large shaded porch, ventilating dormers, large windows, and ventilation under the house.



Figure 10.2q The breezy passage of the dogtrot house was a favorite for both man and beast during the hot and humid summers.



Figure 10.2r Shutters with adjustable louvers were almost universally used in the old South.



Figure 10.2s The Waverly plantation near Columbus, Mississippi, has a large belvedere for view, light, and ventilation. (Photograph by Paul B. Watkins. Courtesy of the Mississippi Department of Economic Development. Division of Tourism.)

The Waverly plantation is a good example of the classical idiom adapted to the climate (Fig. 10.2s). It has a large, many-windowed belvedere, which offers a panoramic view, light, and a strong stack effect through the three-story stair hall. Since every door has operable transoms, all rooms have cross ventilation from three sides (Fig 10.2t). The author visited this non-air-conditioned building on a hot, humid summer day and found it to be comfortably cool inside.

Often the temperate climate is the hardest to design for. This is partly true because many so-called temperate climates actually have very hot summers and very cold winters. Buildings in such climates cannot be designed to respond to either hot or cold conditions alone. Rather, they must be designed for both summer and winter, which often make opposing demands on the architect. The Governor's Mansion in Williamsburg, Virginia, is located in such a climate. The building is compact, and the windows are medium-sized (Fig. 10.2u). The brick construction allows passive cooling during much of the summer when the humidity is low enough. The massive fireplaces act as additional heat sinks in the summer, as well as heat storage mass in the winter. Every room has openings

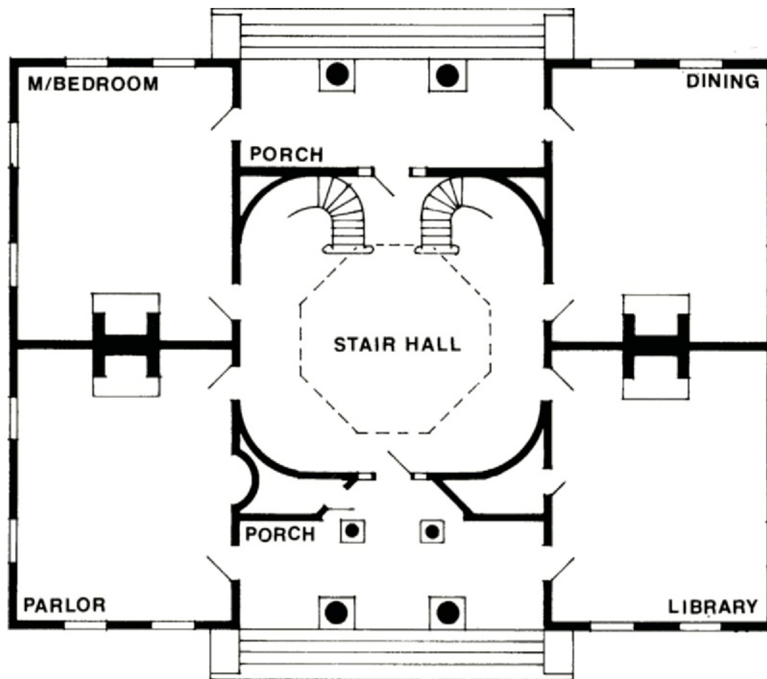


Figure 10.2t A strong stack effect is created by the octagonal belvedere over the open stair hall of the Waverly plantation. All interior doors have transoms. From *Mississippi Houses: Yesterday Toward Tomorrow*, by Robert Ford (copyright).



Figure 10.2u The Governor's Mansion in Colonial Williamsburg, Virginia, is well suited for a temperate climate.

on all four walls for maximum cross ventilation. The little tower on the roof has several different names, depending on its main function. It is a "belvedere" if the panoramic view is most important, it is a "lantern" if it acts primarily as a skylight, it is a "cupola" if it has a small dome on it and is mainly for decoration or image, and it is a "monitor" if ventilation is most important. In the Governor's Mansion, the tower's main purpose was to create the image of a governmental building, but it also served all of the other functions.

Chapter 17 on tropical architecture has many more examples of passive cooling for dry and humid hot climates.

10.3 PASSIVE COOLING SYSTEMS

The passive cooling systems described here include not only the well-known traditional techniques mentioned above but also more sophisticated modern techniques. As much as possible, passive cooling uses natural forces, energies, and heat sinks. When some fans and pumps are used, the systems are sometimes called hybrid. However, the author uses the word "hybrid" only for those systems that use large pumps or fans that use significant amounts of energy.

Since the goal is to create thermal comfort during the summer (the overheated period), we can either (1) cool the building; or (2) raise the comfort zone sufficiently to include the high indoor temperature and humidity (see Fig. 4.9b). In the first case, we have to remove heat from the building by finding a heat sink for it. In the second case, we modify one of the other factors of the thermal environment (i.e., humidity, MRT, or air speed) so that the comfort zone shifts to higher temperatures. In this second case, people will feel more comfortable even though the building is not actually being cooled.

There are five main methods of passive cooling:

Types of Passive Cooling Systems

I. Cooling with Ventilation
  A. Comfort ventilation: Ventilation during the day and night to increase evaporation from the skin and thereby increase thermal comfort.

B. Night-flush cooling: Ventilation to precool the building for the next day.

II. Radiant Cooling
   A. Direct radiant cooling: A building's roof structure cools by radiation to the night sky.
   B. Indirect radiant cooling: Radiation to the night sky cools a heat-transfer fluid, which then cools the building.

III. Evaporative Cooling
   A. Direct evaporation: Water is sprayed into the air entering a building. This lowers the air's temperature but raises its humidity.
   B. Indirect evaporative cooling:
      1. Evaporation cools the incoming air of the building without raising the indoor humidity.
      2. Water is sprayed on the roof to cool the roof.

IV. Earth Cooling
   A. Direct coupling: An earth-sheltered building loses heat directly to the earth.
   B. Indirect coupling: Air enters the building by way of earth tubes.

V. Dehumidification with a desiccant: Latent heat is removed.

A combination of these techniques is sometimes necessary. Each of these techniques will now be discussed in more detail.

10.4 COMFORT VENTILATION VERSUS NIGHT-FLUSH COOLING

Until recently, ventilation was the major cooling technique throughout the world. It is important to note that there are two very different ventilation techniques. Although they cannot be used at the same time, they can be used at different times of the year in climates that are too humid only part of the summer. **Comfort ventilation** brings in outdoor air, both during the day and at night. The air is then passed directly over people to increase evaporative cooling on the skin. Although thermal comfort might be achieved, the daytime air is actually heating the building.

Night-flush cooling is quite different. With this technique, cool night air is introduced to flush out the heat of the building, while during the day very little outside air is brought indoors so that the heat gain to the building is minimized. During the day, the mass of the relatively cool structure acts as a heat sink for the indoor air and the people inside. Before these techniques can be explained in more detail, some basic principles of airflow and their applications in buildings must be discussed.

10.5 BASIC PRINCIPLES OF AIRFLOW

To design successfully for ventilation in the summer or for wind protection in the winter, the following principles of airflow should be understood:

1. *Reason for the flow of air*. Air flows either because of natural convection currents, caused by differences in temperature, or because of differences in pressure (Fig. 10.5a).
2. *Types of airflow*. There are four basic types of airflow: laminar, separated, turbulent, and eddy currents. Figure 10.5b illustrates the four types by means of lines representing airstreams. These diagrams are similar to what one would see in a wind-tunnel test using smoke streams. Airflow changes from laminar to turbulent when it encounters sharp obstructions, such as buildings. Eddy currents are circular airflows induced by laminar airflows (Fig. 10.5e).
3. *Inertia*. Since air has some mass, moving air tends to go in a straight line. When forced to change direction, airstreams will follow curves but never right angles.
4. *Conservation of air*. Since air is neither created nor destroyed at the building site, the air approaching a building must equal the air leaving the building. Thus, lines representing airstreams should be drawn as continuous.
5. *High- and low-pressure areas*. As air hits the windward side of a building, it compresses and creates positive pressure (Fig. 10.5c).

   At the same time, air is sucked away from the leeward side, creating negative pressure. Air deflected around the sides will generally also create negative pressure. Note that these pressures are not uniformly distributed. The type of pressure created over the roof depends on the slope of the roof (Fig. 10.5d). These pressure areas around the building

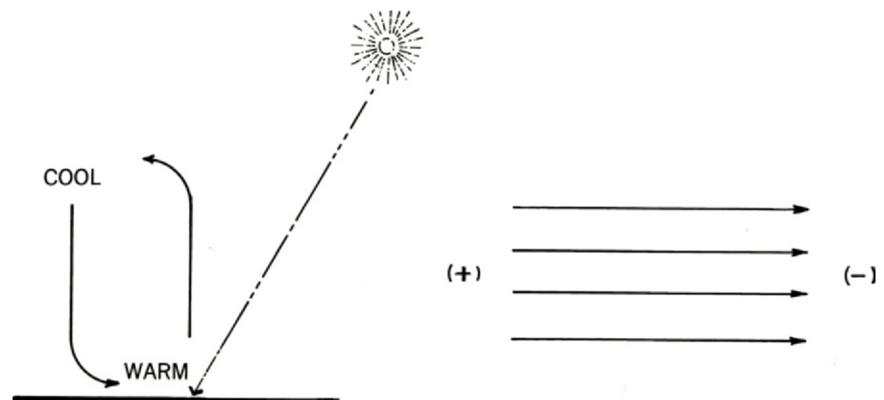


Figure 10.5a Air flows because of either natural convection or pressure differentials.

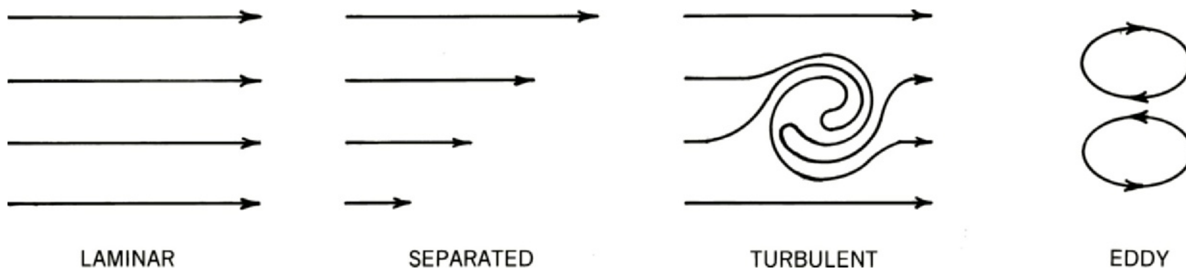


Figure 10.5b The four different kinds of airflow are shown. (After Art Bowen, 1981.)

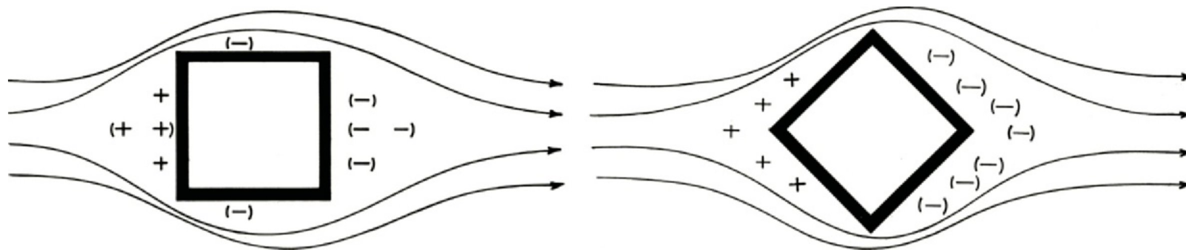


Figure 10.5c Air flowing around a building will cause uneven positive and negative pressure areas to develop. (After Art Bowen, 1981.)

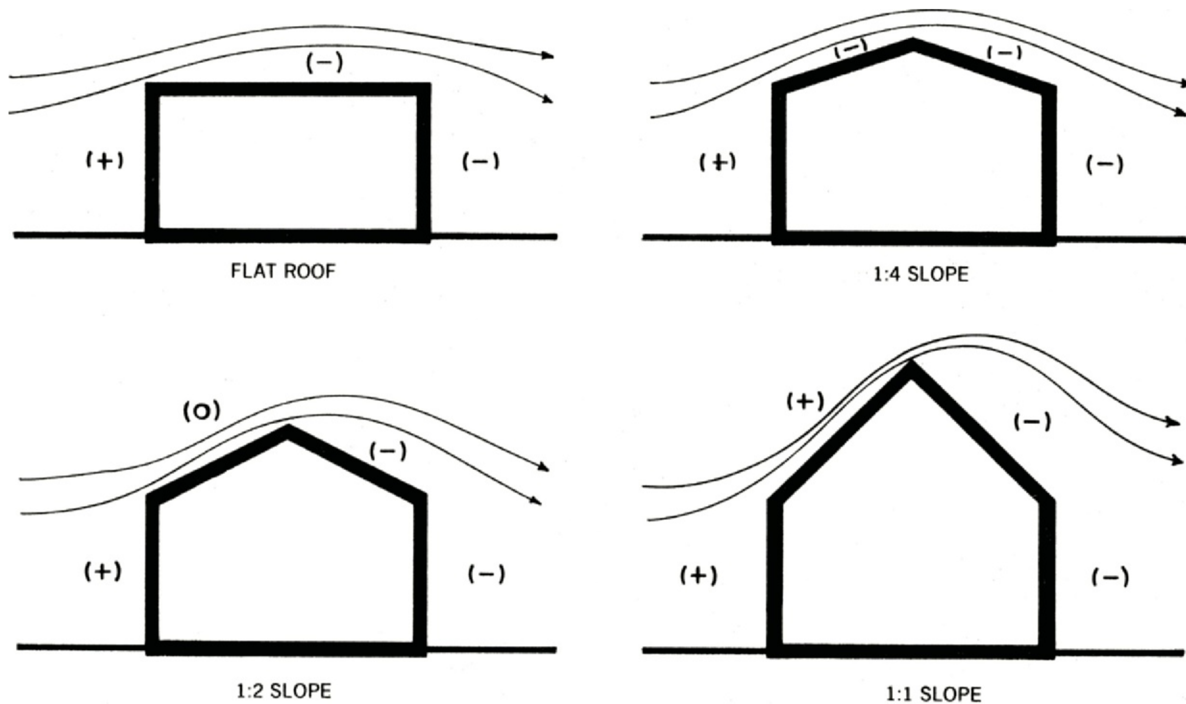


Figure 10.5d The pressure on the leeward side of a roof is always negative, but on the windward side it depends on the slope of the roof. (After Art Bowen, 1981).

determine how air flows through the building.

It should also be noted that these high- and low-pressure areas are not places of calm but of airflow in the form of turbulence and eddy currents (Fig. 10.5e). Note how these currents reverse the airflow in certain locations. For simplicity's sake, turbulence and eddy currents, although usually present, are not shown on all diagrams.

6. *Bernoulli effect*. In the Bernoulli effect, an increase in the velocity of a fluid decreases its static pressure. Because of this phenomenon, there is negative pressure at the constriction of a venturi tube

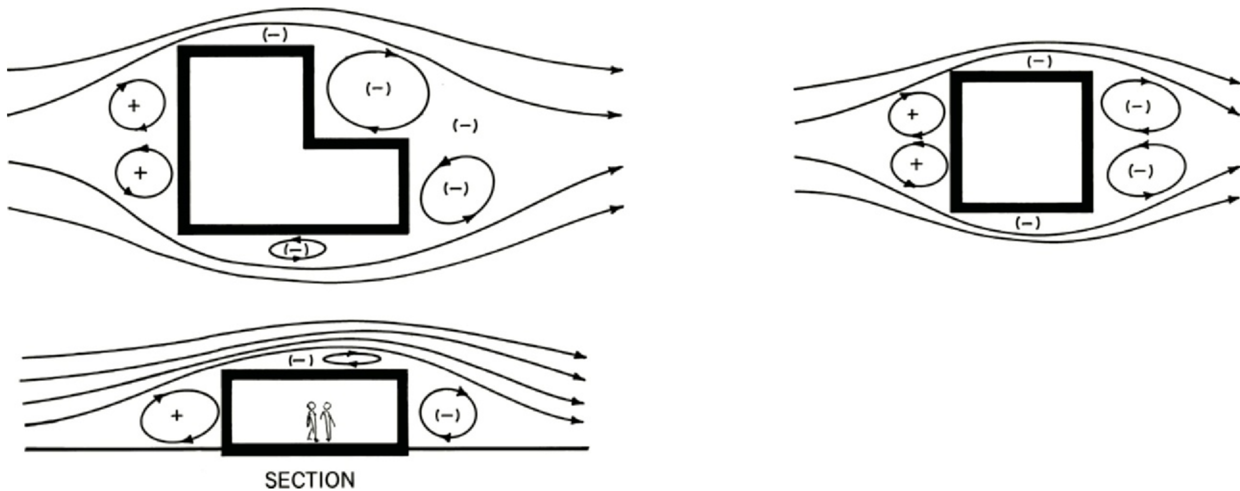


Figure 10.5e Turbulence and eddy currents occur in the high- and low-pressure areas around a building. For simplicity, turbulent air is not shown in any of the diagrams (After Art Bowen, 1981).

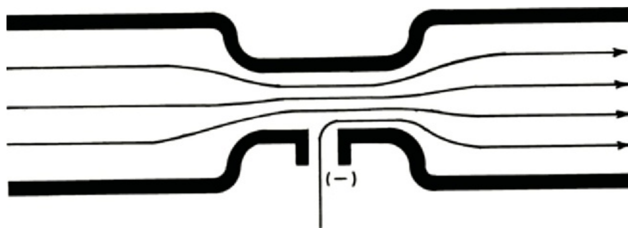


Figure 10.5f The venturi tube illustrates the Bernoulli effect: As the velocity of air increases, its static pressure decreases. Thus, an opening at the constriction would suck in air.

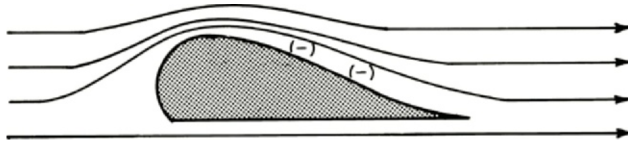


Figure 10.5g An airplane wing is like half of a venturi tube. In this case, the negative pressure is also called lift.

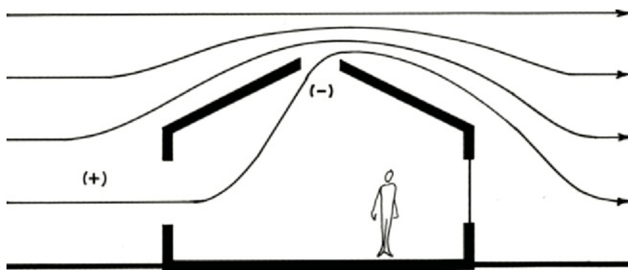


Figure 10.5h The venturi effect causes air to be exhausted through roof openings at or near the ridge.

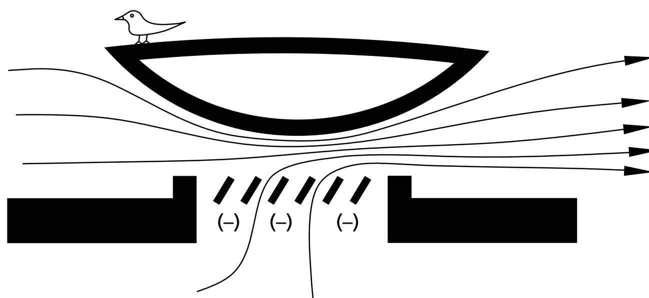


Figure 10.5i Venturi passive ventilators with adjustable louvers are used at the Strasbourg, France, airfreight terminal. Architects: Jockers Architekten, 2001.

(Fig. 10.5f). A cross section of an airplane wing is like half a venturi tube (Fig. 10.5g).

A gabled roof is also like half a venturi tube. Thus, air will be sucked out of any opening near the ridge (Fig. 10.5h). The effect can be made even stronger by designing roof openings to be like full venturi tubes (Fig. 10.5i).

There is another phenomenon at work here. The velocity of air increases rapidly with height above ground. Thus, the pressure at the ridge of a roof will be lower than that of windows at ground level. Consequently, even without the help of the geometry of a venturi tube, the Bernoulli effect will exhaust air through roof openings (Fig. 10.5j).

7. *Stack effect*. The stack effect can exhaust air from a building by the action of natural convection. The stack effect will exhaust air only if the indoor-temperature difference between two vertical openings is greater than the outdoor-temperature difference between the same two openings (Fig. 10.5k). To maximize this basically weak effect, the openings should be as large and as far apart vertically as possible. The air should be able to flow freely from the lower to the higher opening (i.e., minimize obstructions).

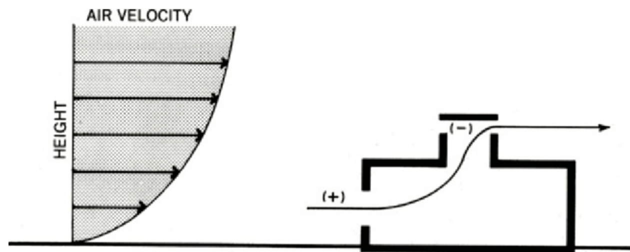


Figure 10.5j Because the air velocity increases rapidly with height above grade, the air has less static pressure at the roof than on the ground (the Bernoulli effect).

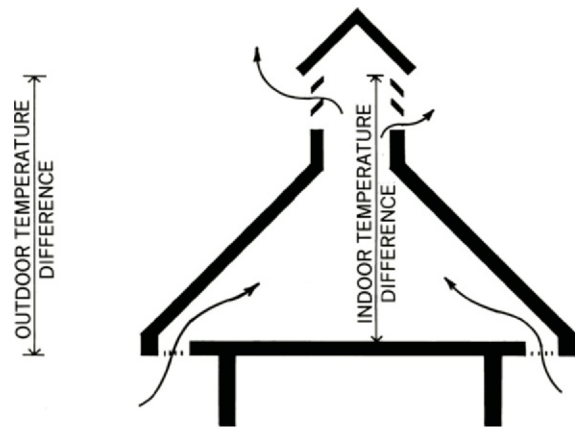


Figure 10.5k The stack effect will exhaust hot air only if the indoor-temperature difference is greater than the outdoor-temperature difference between the vertical openings.

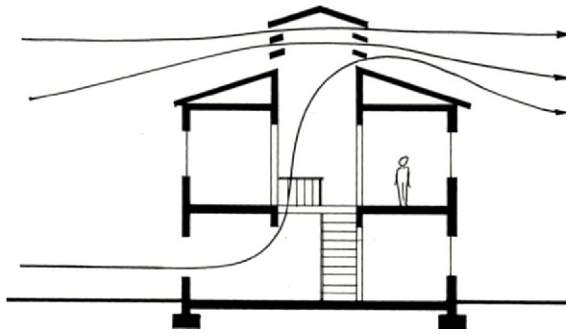
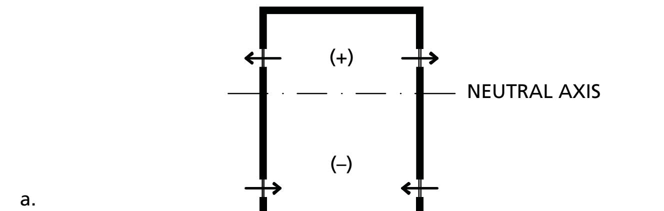
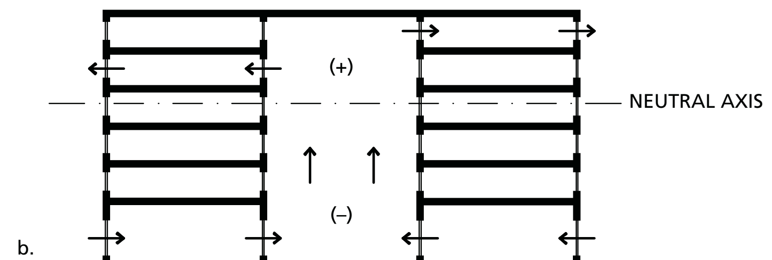


Figure 10.5l The central stair and geometry of this design allow effective vertical ventilation by the combined action of stratification, the stack effect, and both the Bernoulli and venturi effects.





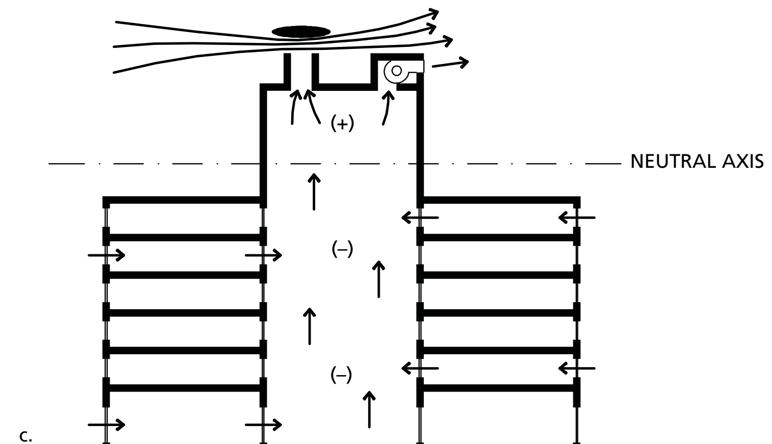


Figure 10.5m The stack effect causes negative pressure in the lower part of a space, positive pressure in the upper part, and zero pressure in between (top drawing). If this space were the atrium of a multistory building, the hot air would enter the upper floors (middle drawing). To avoid this problem, the neutral axis must be raised by increasing the height of the atrium, using wind, and/or exhaust fans (bottom drawing).

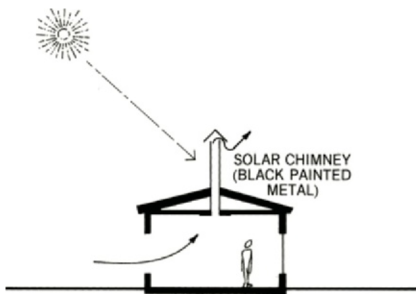


Figure 10.5n A solar chimney increases the stack effect without heating the indoors.

The advantage of the stack effect over the Bernoulli effect is that it does not depend on wind. The disadvantage is that it is a very weak force and cannot move air quickly. It will, however, combine with the Bernoulli and venturi effects mentioned above to create particularly good vertical ventilation on windy hot summer days. Figure 10.5l illustrates how stratification, the stack effect, the shape of the roof (the venturi effect), and the increased wind velocity at the roof (the Bernoulli effect) can combine to ventilate a building naturally. Roof monitors and ventilators high on the roof are especially helpful: because of stratification, the hottest indoor air is exhausted first.

The stack effect causes the lower part of a building with an atrium to have a negative pressure and the upper part to have a positive pressure. Somewhere in between will be the neutral axis (Fig. 10.5m, top). Consequently, hot air from the lower stories enters the upper floors (Fig. 10.5m, middle). To avoid this problem, the neutral axis must be raised above the top floor (Fig. 10.5m, bottom). An interesting application of the stack effect is the **solar chimney**, which can pull hot air out of the building. Since the stack effect is a function of temperature differences, heating the indoor air would increase the airflow, but of course that would conflict with our goal of cooling the indoor air. Therefore, the solar chimney heats the air above the building, thereby creating a negative pressure, which pulls out indoor air (Figs. 10.5n). Thus, the stack effect is increased without additional heating of the building.

Maximize the vertical height between openings to promote the stack effect!

10.6 AIRFLOW THROUGH BUILDINGS

The following factors determine the pattern of airflow through a building: pressure distribution around the building; direction of air entering windows; size, location, and details of windows; and interior partitioning details. Each of these factors will be considered in more detail.

Site Conditions

Adjacent buildings, walls, and vegetation on the site will greatly affect the airflow through a building. These site conditions will be discussed in Chapter 11.

Window Orientation and Wind Direction

Winds exert maximum pressure when they are perpendicular to a surface, and the pressure is reduced about 50 percent when the wind is at an oblique angle of about 45°. However, the indoor ventilation is often better with the oblique winds because they generate greater wind motion indoors (Fig 10.6a). Consequently, a fairly large range of wind directions will work for most designs. This is fortunate because it is a rare site that has winds blowing mainly from one direction. Even where there are strong prevailing directions, it might not be possible to face the building into the wind.

In most climates, the need for summer shade and winter sun calls for a building orientation with the long axis in the east–west direction, and Figure 10.6b shows the range of wind directions that works well with that orientation. Even when winds are east–west, the solar orientation usually has priority because winds can be rerouted more easily than the sun (Fig. 10.6c).

Window Locations

Cross ventilation is very effective because air is both pushed and pulled through the building by a positive pressure on the windward side and a negative pressure on the leeward side (Fig. 10.6d). Ventilation from windows on adjacent walls can be either good or bad, depending on the pressure distribution, which varies with wind direction (Fig. 10.6e).

Ventilation from windows on one side of a building can vary from fair to poor, depending on the location of windows. Since the pressure is greater at the center of the windward wall than at the edges, there is some pressure difference in the asymmetric placement of windows, while there is no pressure difference in the symmetric scheme (Fig. 10.6f).

Fin Walls

Fin walls can greatly increase the ventilation through windows on the same side of a building by changing the pressure distribution (Fig. 10.6g).

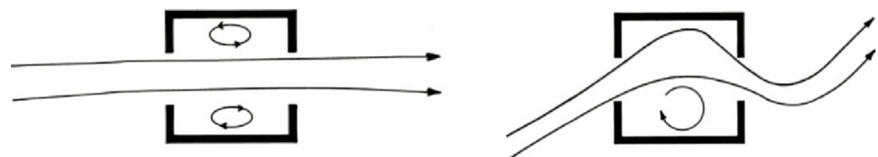


Figure 10.6a Usually indoor ventilation is better from oblique winds than from head-on winds because the oblique airstream covers more of the room.

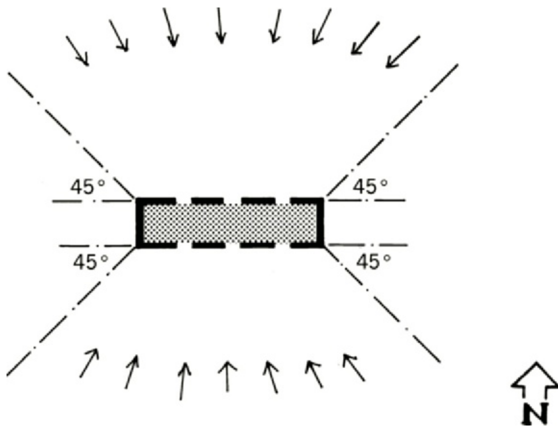


Figure 10.6b Acceptable wind directions for the orientation that is best for summer shade and winter sun.

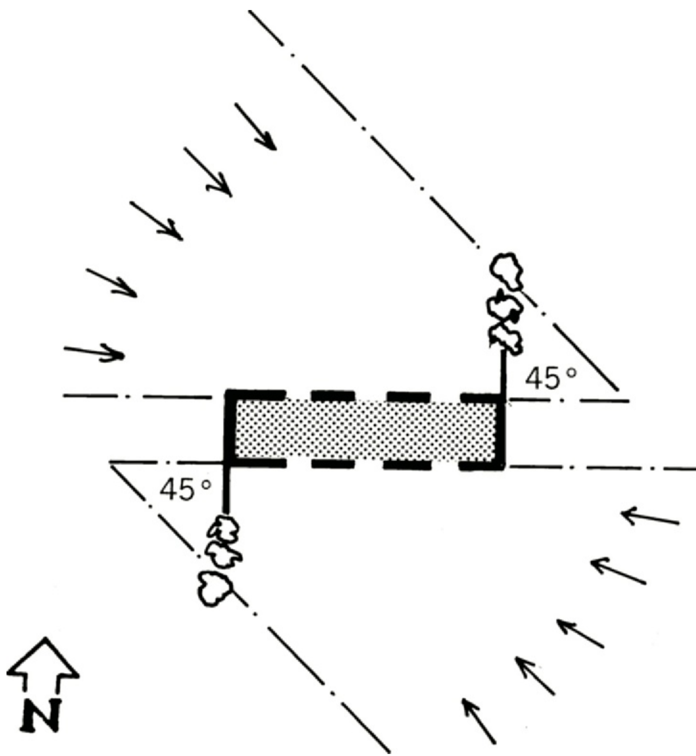


Figure 10.6c Deflecting walls and vegetation can be used to change airflow direction so that the optimum solar orientation can be maintained.

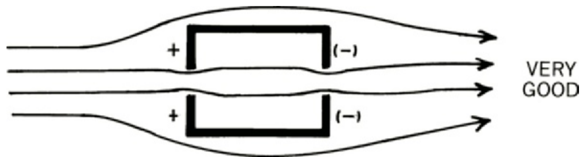


Figure 10.6d Cross ventilation between windows on opposite walls is the ideal condition.

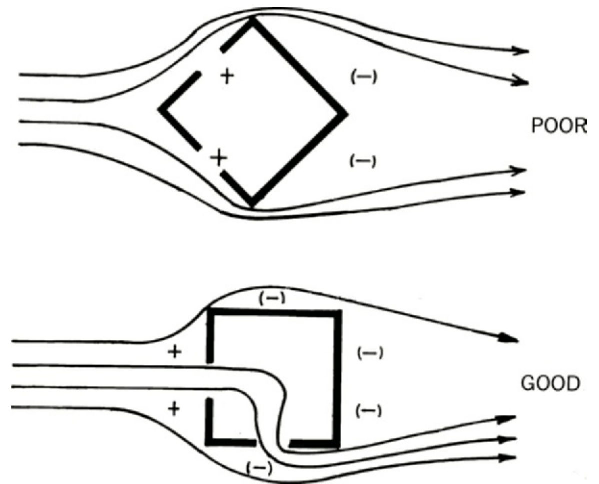


Figure 10.6e Ventilation from windows on adjacent sides can be poor or good, depending on wind direction.

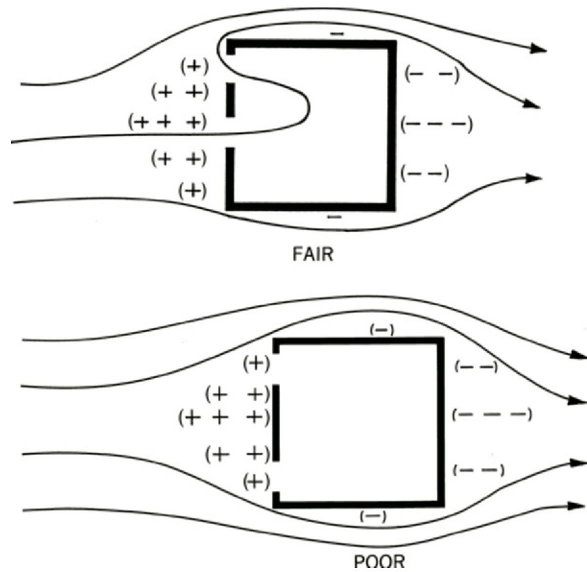


Figure 10.6f Some ventilation is possible in the asymmetric placement of windows because the relative pressure is greater at the center than at the sides of the windward wall. (After Art Bowen, 1981.)

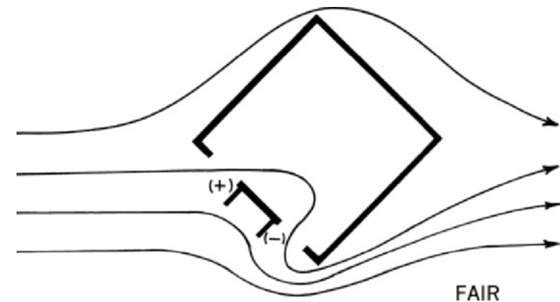


Figure 10.6g Fin walls can significantly increase ventilation through windows on the same wall. (After Art Bowen, 1981.)

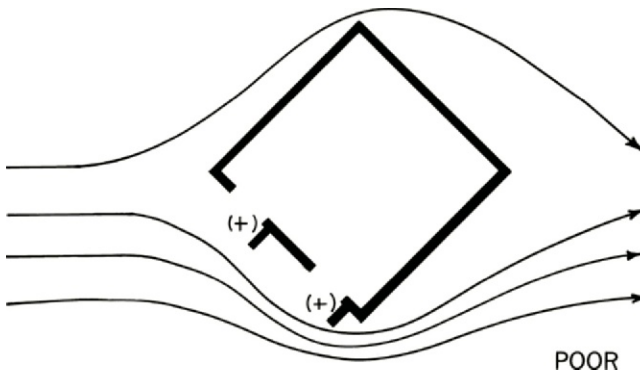


Figure 10.6h Poor ventilation results from fin walls placed on the same side of each window or when two fins are used on each window.

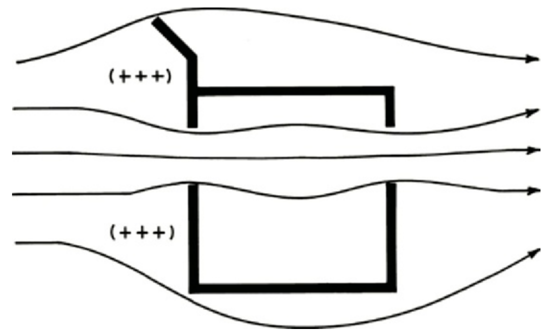


Figure 10.6j A fin wall can be used to direct the airstream through the center of the room, as seen in this plan view.

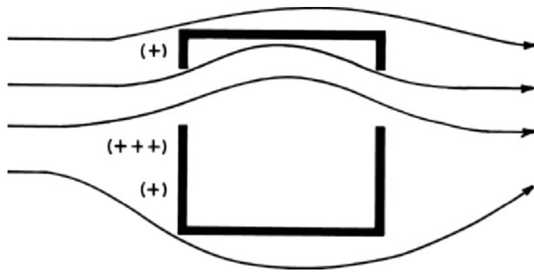


Figure 10.6i The greater positive pressure on one side of the window deflects the airstream in the wrong direction. Much of the room remains unventilated.

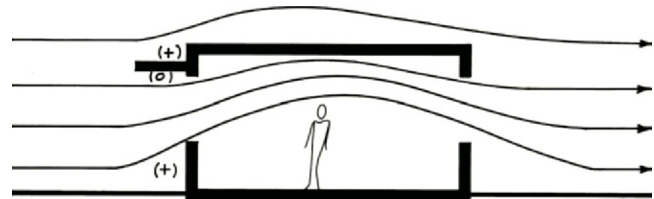


Figure 10.6k The solid horizontal overhang causes the air to deflect upward. (After Art Bowen, 1981.)

Note, however, that each window must have only a single fin. Furthermore, fin walls will not work if they are placed on the same side of each window (Fig. 10.6h). Fin walls work best for winds at 45° to the window wall. Casement windows can act as fin walls at no extra cost.

The placement of windows on a wall determines not only the quantity but also the initial direction of the incoming air. The off-center placement of the window gives the airstream an initial deflection because the positive pressure is greater on one side of the window (Fig. 10.6i). To better ventilate the room, one should deflect the airstream in the opposite direction. A fin wall can be used to change the pressure balance and, thus, the direction of the airstream (Fig. 10.6j).

Horizontal Overhangs and Airflow

A horizontal overhang just above the window will cause the airstream to deflect up to the ceiling because the solid overhang prevents the positive pressure above it from balancing the positive pressure below the window (Fig. 10.6k). However, a louvered overhang or gap of 6 in. (15 cm) or more in the overhang will allow the positive pressure above it to affect the direction of the airflow (Fig. 10.6l). Placement of the overhang higher on the wall can also direct the airstream down to the occupants (Fig. 10.6m). The design shown in Figure 10.6k is appropriate for night-flush cooling since it sends the air up to cool the structure, while the designs shown in Figures 10.6l, 10.6m, and 10.6o would be appropriate for comfort ventilation because the air passes over people.

Window Types

The type and design of windows have a great effect on both the quantity and direction of airflow. Although double-hung, single-hung, and sliding windows do not change the direction of the airstream, they do block at least 50 percent of the airflow. Casement windows, on the other hand, allow almost full airflow, but they can deflect the airstream (Fig. 10.6n). They also act as fin walls, as described above.

For the vertical deflection of the airstream, use hopper, awning, or jalousie windows (Fig. 10.6n). These types also deflect the rain while still admitting air, which is very

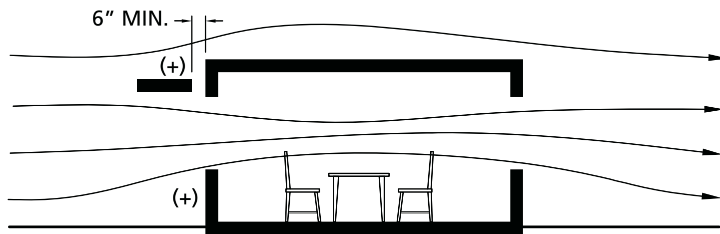


Figure 10.6l A louvered overhang or a gap in the overhang will permit the airstream to straighten out.

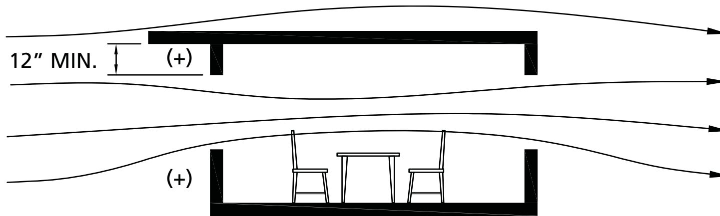


Figure 10.6m A solid horizontal overhang placed high above the window will also straighten out the airstream. (After Art Bowen, 1981.)

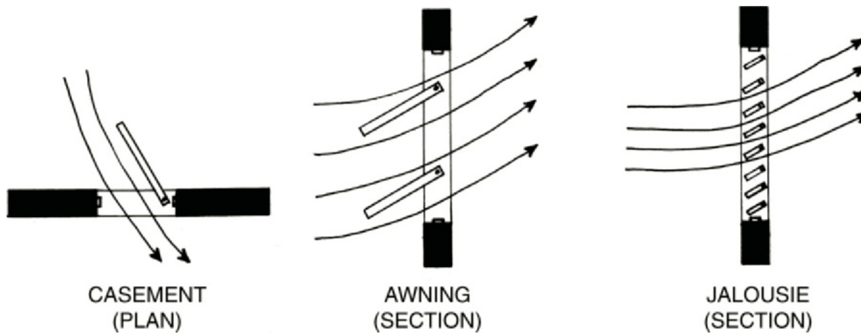


Figure 10.6n All but double-hung and sliding windows have a strong effect on the direction of the airstream.

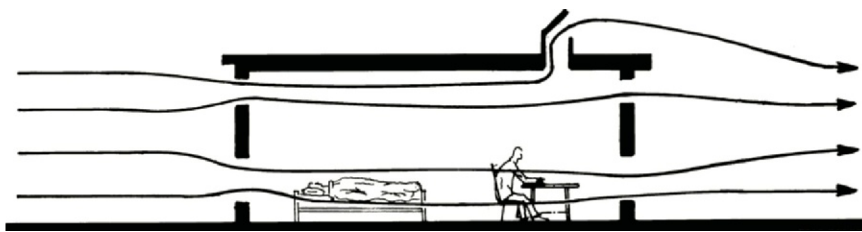


Figure 10.6o For comfort ventilation, openings should be at the level of the occupants. High openings vent the hot air collecting near the ceiling and are most useful for night-flush cooling. (After Art Bowen, 1981.)

important in hot and humid climates. Unfortunately, with this kind of inclination, the windows deflect the wind upward over people's heads, which is undesirable for comfort ventilation. However, if a large overhang keeps the rain out, then the slats of the jalousie windows can be set to be horizontal.

Movable opaque louvers, frequently used on shutters, are like jalousie windows except that they also block the sun and view. The large amount of crack and resultant infiltration makes these types of windows and louvers inappropriate in climates with cold winters.

Vertical Placement of Windows

The purpose of the airflow will determine the vertical placement and height of windows. For comfort ventilation, the windows should be low, at the level of the people in the room. That places the windowsill between 1 and 2 ft (30 and 60 cm) above the floor for people seated or reclining. Additional high windows or ceiling vents should be considered for exhausting the hot air that collects near the ceiling (Fig. 10.6o). High openings are also important for night-flush cooling where air must pass over the structure of the building.

Traditional buildings in the South had windows that were almost the full height of the room. Thomas Jefferson's home, Monticello, in Virginia, had triple-hung windows that went from the floor to the ceiling. By being triple-hung, the windows' upper and lower sashes could be opened for maximum ventilation. Jefferson could also raise the lower two sashes to create a door to the porch.

It is often advantageous to place windows high on a wall in very tall places where they are too high to reach for direct manual operation. Mechanical devices are readily available for both manual and automatic operation. Some work with mechanical linkage (Fig. 10.6p) and others with electric motors (Figs. 10.6q and 10.6r).

Inlet and Outlet Sizes and Locations

Generally, the inlet and outlet size should be about the same, since the amount of ventilation is mainly a function of the smaller opening. However, if one opening is smaller, it

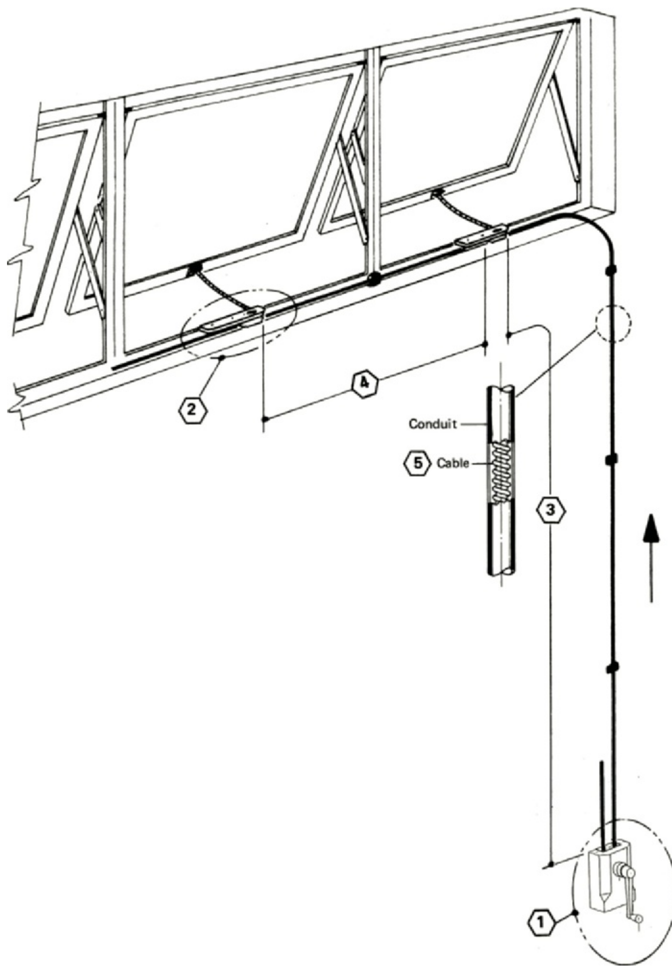


Figure 10.6p One type of mechanical linkage for operating high windows. (Courtesy of Clearline Inc.)



Figure 10.6q Each motor opens a bank of awning windows by rotating a shaft that extends the whole length of the window wall.

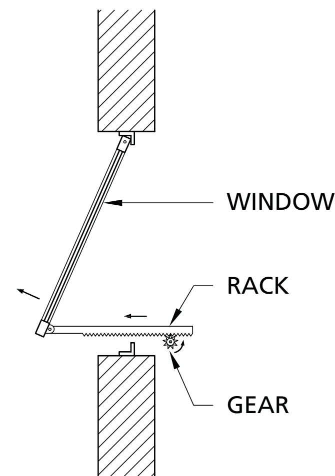


Figure 10.6r A common way to open remote windows is with the rack-and-pinion mechanism. An electric motor turns a shaft with gears (pinions), which are meshed with a rack on each side of each window. Thus, the windows can be closed or opened by rotating the shaft clockwise or counterclockwise. The same motor and shaft can open and close windows the whole length of the building.

should usually be the inlet, because that maximizes the velocity of the indoor airstream, and it is the velocity that has the greatest effect on comfort. Although velocities higher than the wind can be achieved indoors by concentrating the airflow, the area served is, of course, decreased (Fig. 10.6s). The inlet opening not only determines the velocity, but also determines the airflow pattern in the room. The location of the outlet, on the other hand, has little effect on the air velocity and flow pattern.

However, because many locations have no prevailing wind, most naturally ventilated buildings must be designed to function under many different wind directions. Thus, it is usually best to have inlets and outlets the same size.

Insect Screens

Airflow is decreased about 50 percent by an insect screen. The actual resistance is a function of the angle at which the wind strikes the screen, with the lowest resistance for a head-on wind. To compensate for the effect of the screen, larger window openings are required. A screened-in porch is especially effective because of the very large screen area that it provides (Fig. 10.6t).

Roof Vents

Passive roof ventilators are typically used to lower attic temperatures. If, however, local winds are high enough, and the ventilator is large

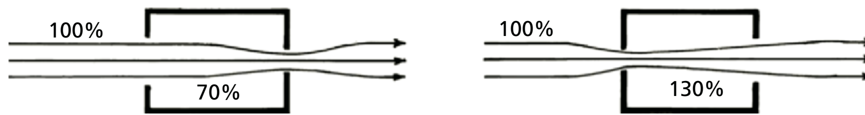


Figure 10.6s Inlets and outlets should be the same size. If they cannot be the same size, the inlet should be smaller to maximize the velocity. (After Art Bowen, 1981.)

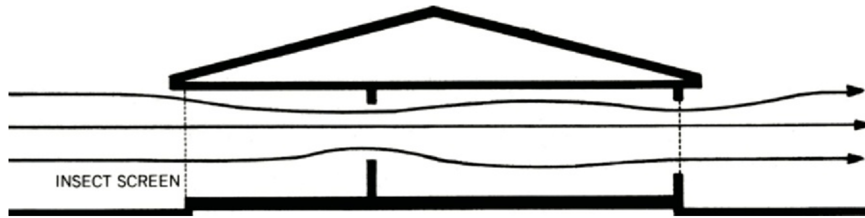


Figure 10.6t The resistance to airflow by insect screens can be largely overcome by means of larger openings or screened-in porches.

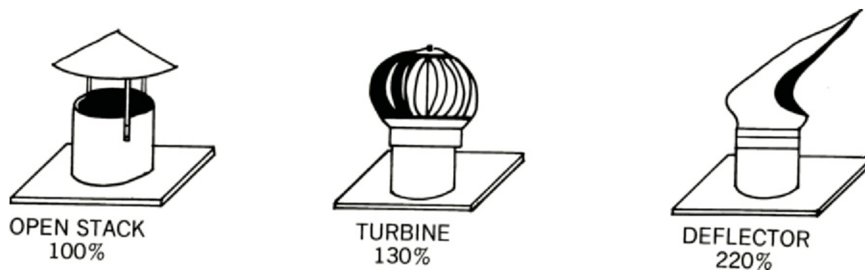


Figure 10.6u The design of a roof ventilator has a great effect on its performance. The percentages shown indicate relative effectiveness. To maximize negative pressure, the deflector rotates so that the opening is always leeward. (After Shubert and Hahn, 1983.)

enough or high enough on the roof, these devices can also be used to ventilate habitable spaces. The common wind turbine enhances ventilation about 30 percent over an open stack. Research has shown that other designs can enhance the airflow as much as 120 percent (Fig. 10.6u).

Although the BRE office building uses the simpler open-stack ventilators, significant ventilation is achieved by the height of the opening (Fig. 10.6v). A very sophisticated type of ventilator called a cowl is used at the BedZED housing development (Fig. 10.6w). A large vane aligns the cowl with the wind so that air is both pushed and pulled through the building. The windward opening experiences a positive pressure, while the leeward opening experiences a negative pressure. Complex ducting from the cowl sends the air throughout the building for ventilation.

Although cupolas, monitors, and roof vents are often a part of traditional architecture (see Figs. 10.2t and 10.2v), they can also be integrated very successfully into modern architecture (Figs. 10.6v–10.6z). Some



Figure 10.6v The Building Research Establishment (BRE) office building uses open stacks with great height to maximize both the stack effect and wind effect to ventilate the building naturally. Architect: Fielden Clegg. Location: Garston, England, 1991–1997. (Photo: Bruce Haglund.)



Figure 10.6w The Beddington Zero Energy Development (BedZED) in London, England, uses rotating ventilators to maximize the air exhausted from the building by the wind. Architects: Bill Dunster Architects. Engineers: ARUP. (Photo courtesy of ARUP.)



Figure 10.6x The Animal Foundation Dog Adoption Park uses monitors placed high and oriented to the local winds to maximize the natural ventilation. Location: Las Vegas, Nevada, 2005. Architect: Tate Snyder Kimsey.



Figure 10.6y Monitors on the roofs of the bathing pavilions at Callaway Gardens, Georgia.

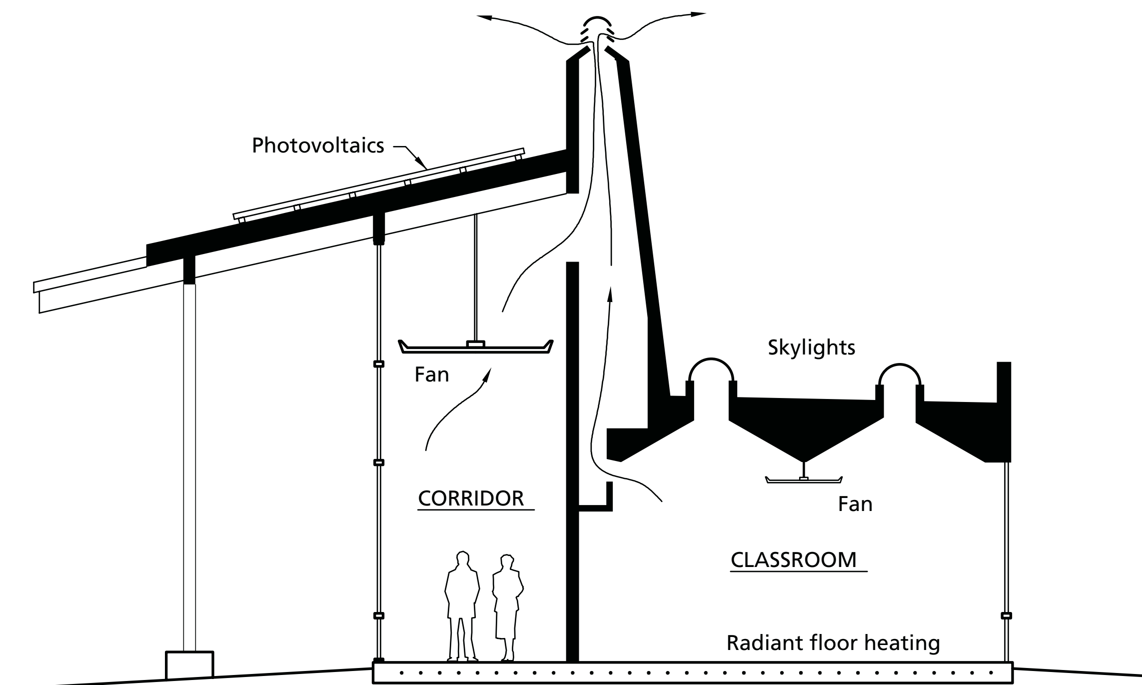


Figure 10.6z This extension to the Portland Community College uses a series of ventilation stacks as a passive cooling strategy. Ceiling fans are used for additional comfort.

kind of shutter or trapdoor is required to prevent unwanted ventilation, especially in the winter.

Fans

In most climates, wind is not always present in sufficient quantity when needed, and usually there is less wind at night than during the day. Thus, fans are often required to augment the wind.

There are three quite different purposes for fans. The first is to exhaust hot, humid, and polluted air. This is part of the heat-avoidance strategy and is discussed in Chapter 15. The second is to bring in outdoor air to either cool people (comfort ventilation) or cool the building at night (night-flush cooling). The third purpose is to circulate indoor air at those times when the indoor air is cooler than the outdoor air.

Separate fans are required for each purpose. Window or whole-house fans are used for comfort ventilation or night-flush cooling (Fig. 10.6aa). Ceiling or table fans are used whenever the indoor air is cooler and/or less humid than the outdoor air.

Because ceiling fans with flat blades are inefficient, use only fans with airfoil blades, which move more air more effectively with less energy. Also, large, slow-moving ceiling fans are much more efficient than small, fast-moving ones. In winter the ceiling fans can be run in reverse to bring warm air down. By blowing cooler air up to the ceiling, the warm air collecting there is pushed sideways to the walls and then down to the floor. However, This antistratification method increases comfort and reduces heat loss through the roof the winter use of ceiling fans will not work in very high or wide spaces.

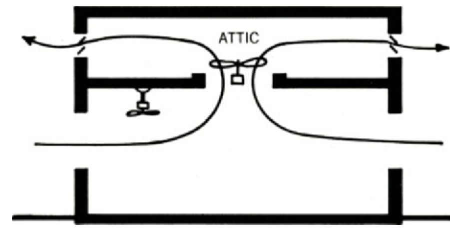


Figure 10.6aa Whole-house or window fans are used to bring in outdoor air for either comfort ventilation or night-flush cooling. Ceiling or table fans are mainly used when the air temperature and humidity are lower indoors than outdoors.

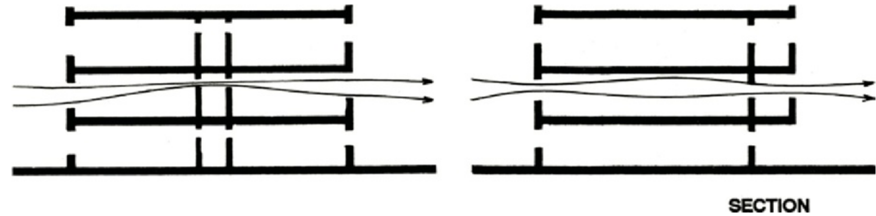


Figure 10.6bb In regard to natural ventilation, single-loaded corridor plans (right) are far superior to double-loaded plans (left), even if transoms are used.

Partitions and Interior Planning

Open plans are preferable because partitions increase the resistance to airflow, thereby decreasing total ventilation. When partitions are used but are in one apartment or one tenant area, cross ventilation is often possible by leaving doors open between rooms. Cross ventilation is almost never possible, however, when a public double-loaded corridor plan is used. Before air-conditioning became available, transoms (windows above doors) allowed for some cross ventilation, but with the loss of acoustic privacy and odor containment.

An alternative to the double-loaded corridor is the open single-loaded corridor, since it permits full cross ventilation (Fig. 10.6bb). One important drawback of single-loaded corridors is the lack of privacy, since half of the windows in each apartment face the public corridor (balcony). Two ingenious modifications provide privacy in single-loaded designs (Fig. 10.6cc and 10.6dd). Single-story buildings can improve on the double-loaded

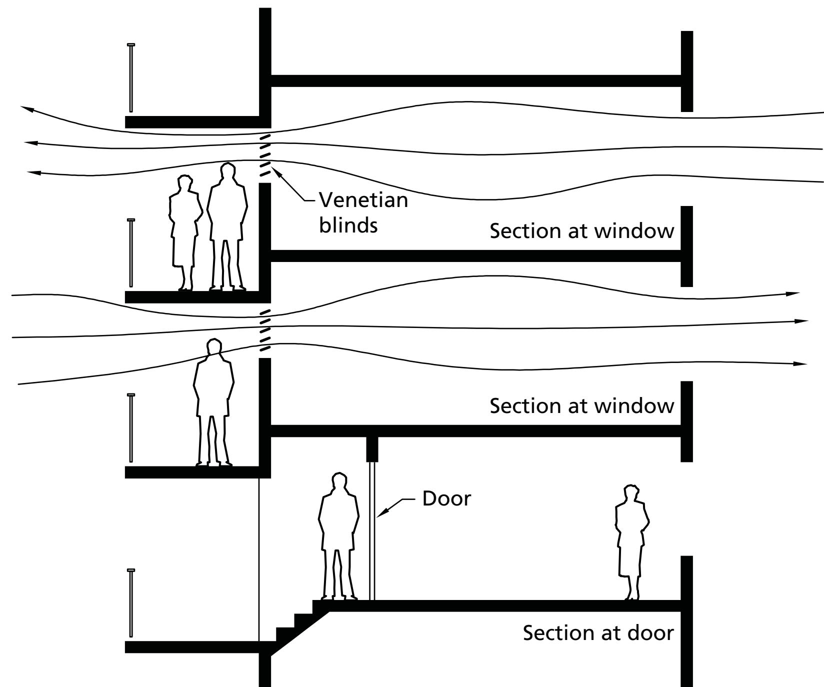


Figure 10.6cc By dropping the outdoor corridor several steps below the apartment floors, privacy is improved while maintaining cross ventilation.

corridor by using clerestory windows instead of transoms (Fig. 10.6ee).

Le Corbusier came up with an ingenious solution for cross ventilation in his Unité d'Habitation at Marseilles (Fig. 10.6ff). The building has a corridor on only every third floor, and each apartment is a duplex with an opening to the corridor as well as the opposite sides of the building (Fig. 10.6gg). The balconies have perforated parapets to further encourage ventilation, and they form a giant brise-soleil for sun shading. Le Corbusier opened the

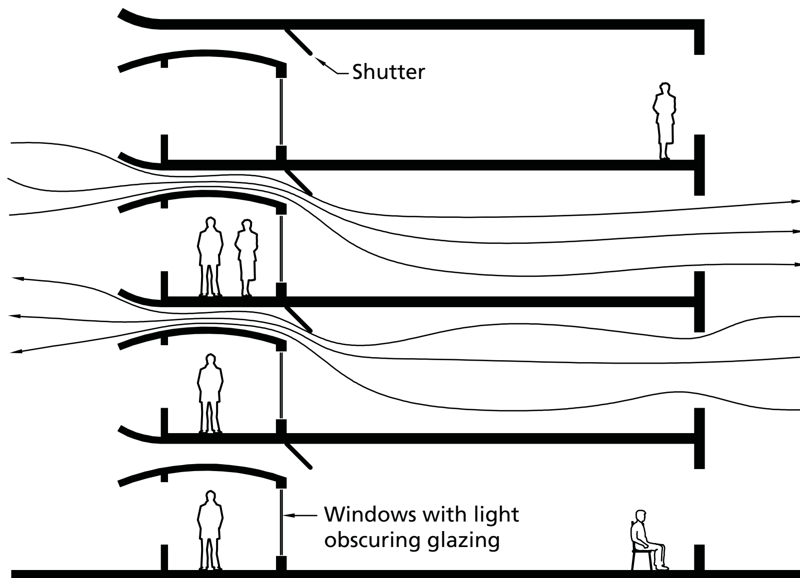


Figure 10.6dd A narrow but continuous slot above the outdoor corridor can allow cross ventilation while providing complete privacy. The corridor windows can contain light-transmitting but image-obscuring glazing.



Figure 10.6ff The Unité d'Habitation at Marseilles, France, was designed by Le Corbusier to provide cross ventilation for each apartment. (Photograph by Alan Cook.)

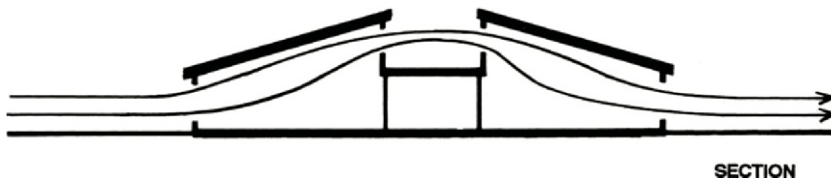


Figure 10.6ee In single-story buildings, a double-loaded corridor plan can use clerestory windows instead of transoms for cross ventilation.

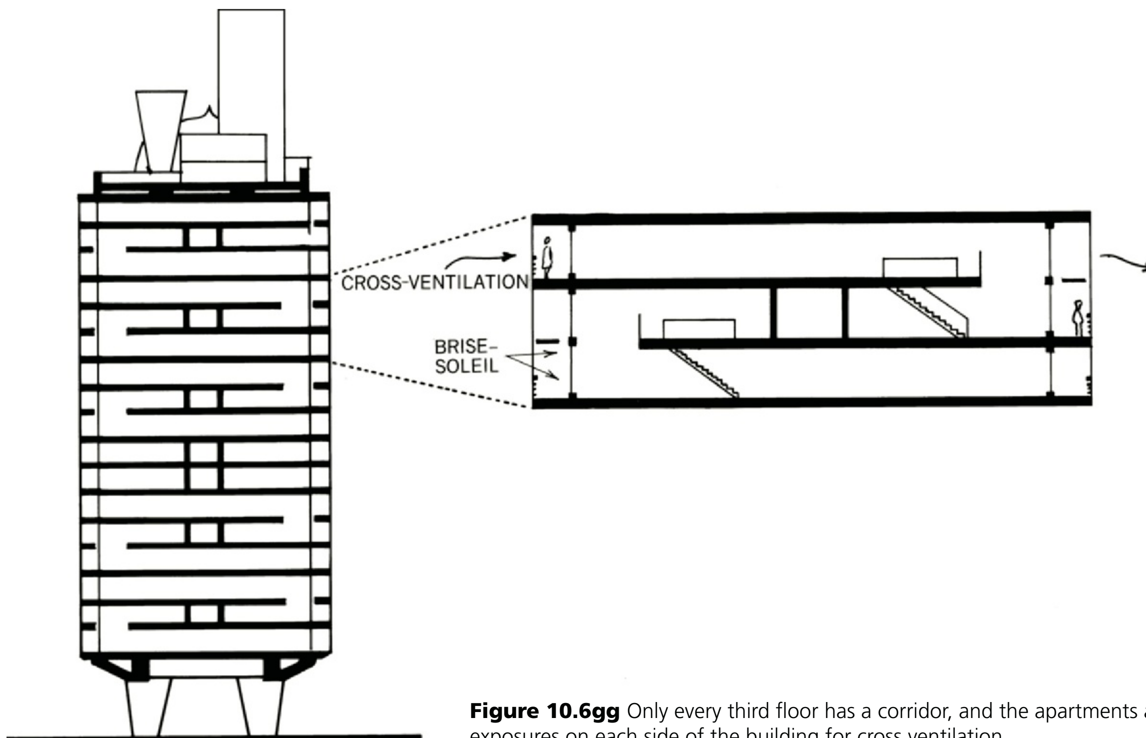


Figure 10.6gg Only every third floor has a corridor, and the apartments are all duplexes with exposures on each side of the building for cross ventilation.

area under the building to the wind by resting the building on columns that he called *pilotis*. In a hot climate, such an area becomes a cool, breezy place in summer, but in a cold climate the same area becomes very unpleasant in the winter. The wind patterns around buildings will be discussed further in Chapter 11.

10.7 EXAMPLE OF VENTILATION DESIGN

Ventilation design is greatly aided by the use of airflow diagrams. These diagrams are based on the general principles and rules mentioned above and not on precise calculations. They are largely the product of a trial-and-error process. The following steps are a guide to making these airflow diagrams.

Airflow Diagrams

1. Determine a common summer-wind direction from local weather data or from the wind roses given in Figure 5.6f.
2. On an overlay of the plan and site, draw a series of arrows parallel to the chosen wind direction on the upwind side of the building and their continuation on the downwind side. (Fig. 10.7a). These arrows should be spaced about the width of the smallest window.
3. By inspection, determine the positive- and negative-pressure areas around the building and record these on the overlay (Fig. 10.7a).
4. By means of a trial-and-error process, trace each windward arrow through or around the building to meet its downwind counterpart. Lines should not cross, end, or make sharp turns. Airflow through the building should go from positive- to negative-pressure areas (Fig. 10.7b).
5. When the airstream is forced to flow vertically to another floor plan, show the point where it leaves any plan by a circle with a dot and the return point by a circle with a cross (Fig. 10.7b). Also show the vertical movement in a section of the building (Fig. 10.7c).
6. Since spaces that are not crossed by airflow lines might not receive enough ventilation, relocate windows, add fins, etc., to change the airflow pattern as necessary.
7. Repeat steps 2 to 6 until a good airflow pattern has been achieved.

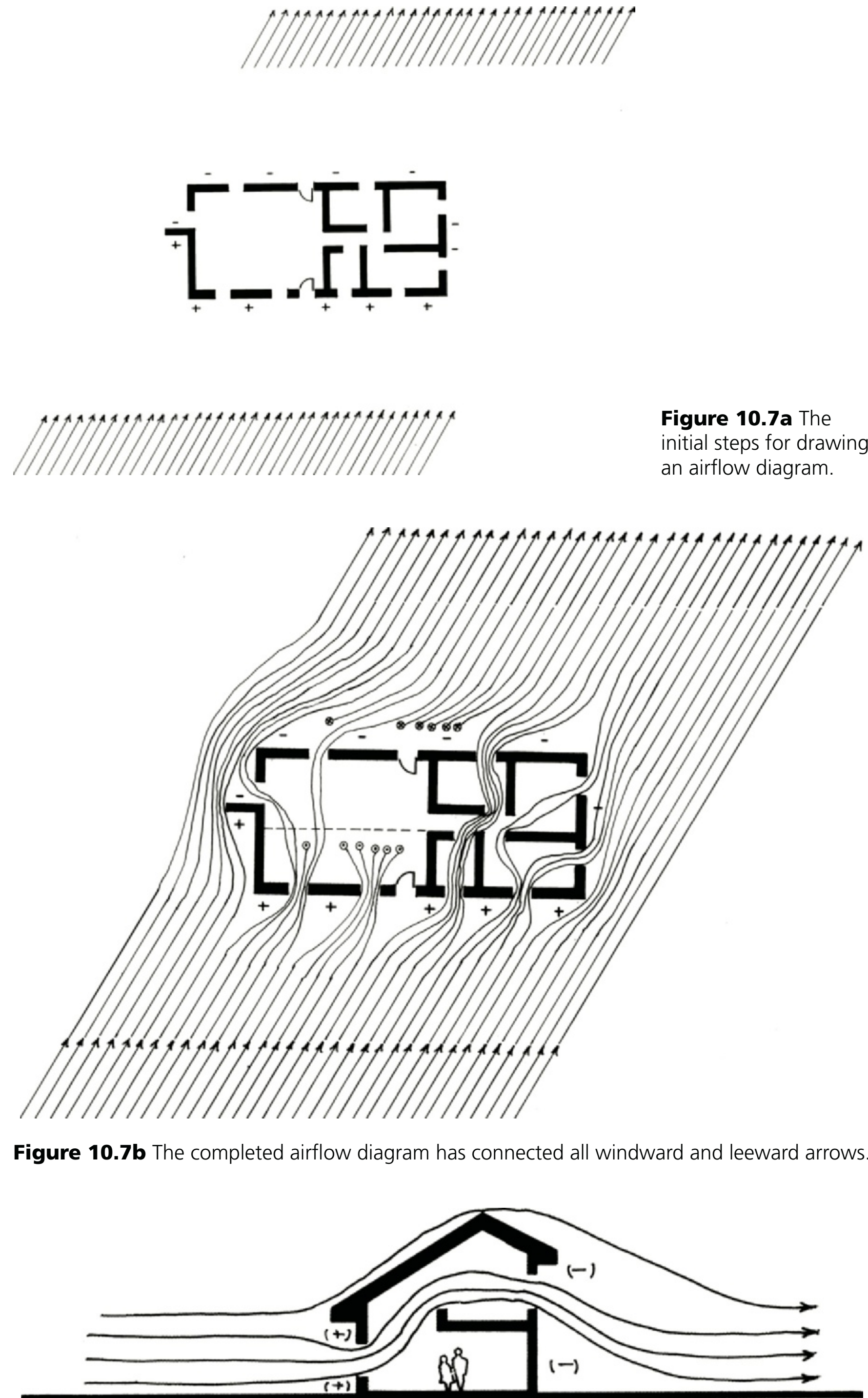


Figure 10.7a The initial steps for drawing an airflow diagram.

Figure 10.7b The completed airflow diagram has connected all windward and leeward arrows.

Figure 10.7c Airflow should also be checked in section. (This technique is based on work by Prof. Murray Milne, UCLA.)



Figure 10.7d This water table at Chiang Mai University in Thailand allows effective ventilation studies by using streams of colored water to simulate airflow through a building. See Appendix G for more information about the water table. (Photo of and by Prof. Ruht Tantachamroon)

This technique is based on work by Prof. Murray Milne, UCLA.

Ventilation can also be designed and tested with a water table apparatus, as shown in Figure 10.7d. Water flow is used as an analogy for wind. A section of the building is modeled in slight three dimensions about ¾ in. (2 cm) thick. Water is thus allowed to flow through the model. When narrow streams of dye are added to the water supply, it quickly becomes apparent to what extent water flows through the model, thereby indicating how the wind will flow through the building. See Appendix G for a full description of the water table and for detailed construction drawings.

10.8 COMFORT VENTILATION

Air passing over the skin creates a physiological cooling effect by evaporating moisture from the surface of the skin. The term **comfort ventilation** is used for this technique of using air motion across the skin to promote thermal comfort. This passive cooling technique is useful for certain periods of the day and year in most climates, but it is especially appropriate in hot and humid climates, where it is typical for the coincident air temperature and relative humidity to be outside the comfort zone. Often, air motion can move the comfort zone sufficiently to create thermal comfort (see Fig. 4.9b). Also see Figure 4.12 for the conditions under which comfort ventilation is appropriate.

Comfort ventilation can rarely be completely passive because in most climates winds are not always sufficient to create the necessary indoor air velocities. Window or whole-house attic fans are usually needed to supplement the wind. See Table 10.8 for the effect on comfort due to various air velocities. For comfort ventilation, the airflow techniques mentioned above should be used to maximize the airflow across the occupants of the building.

If the climate is extremely humid, if little or no heating is required, and

Table 10.8 Air Velocities and Thermal Comfort

Air Velocity				Equivalent Temperature Reduction*		
I-P		SI				
fpm	*mph*	*m/s*	*kph*	°*F*	°*C*	Effect on Comfort
10	0.1	0.05	0.2	0	0	Stagnant air, slightly uncomfortable
40	0.5	0.2	0.8	2	1.1	Barely noticeable but comfortable
50	0.6	0.25	1.0	2.4	1.3	Design velocity for air outlets that are near occupants
80	1	0.4	1.6	3.5	1.9	Noticeable and comfortable
160	2	0.8	3.2	5	2.8	Very noticeable but acceptable in certain high-activity areas if air is warm
200	2.3	1.0	3.7	6	3.3	Upper limit for air-conditioned spaces Good air velocity for natural ventilation in hot and dry climates
400	4.5	2.0	7.2	7	3.9	Good air velocity for comfort ventilation in hot and humid climates
900	10	4.5	16	9	5.0	Considered a gentle breeze when felt outdoors

*The values in this column are the number of degrees that the temperature would have to drop to create the same cooling effect as the given air velocity.

if air-conditioning will not be used, lightweight construction is appropriate. In such climates, any thermal mass will only store up the heat of the day to make the nights less comfortable (Fig 10.8a). In the United States, only southern Florida and Hawaii (climate region 16) fit in this category. In these climates, a moderate amount of insulation is still required to keep the indoor surfaces from getting too hot due to the action of the sun on the roof and walls. The insulation keeps the mean radiant temperature (MRT) from rising far above the indoor air temperature, since that would decrease thermal comfort. However, if the walls are fully shaded, less insulation will be needed. Insulation is also required when the building is air-conditioned. Thermal mass is helpful for buildings that are mostly air-conditioned even in humid climates. It allows the air-conditioning to be turned off during times of peak electrical demand, because the mass will prevent quick temperature changes. The building can also be precooled during the night.

Some control is also possible over the temperature of the incoming air. For example, tests have shown that when the air temperature above unshaded asphalt was 110°F (43°C), it was only 90°F (32°C) over an adjacent shaded lawn. The lower the incoming air temperature, the more effective comfort ventilation will be.

For comfort ventilation, the operable window area should be at least 20 percent of the floor area, with the openings split about equally between windward and leeward walls. The windows should also be well shaded on the exterior, as explained in Chapter 9. One of the examples presented there was Frank Lloyd Wright's Robie House (Fig. 9.1i). It has very large roof overhangs to shade walls made entirely of glass doors and windows that can be opened for ventilation (Fig. 10.8b). Since Chicago has very hot and humid summers, plentiful ventilation and full shade were the major cooling strategies before air-conditioning became available.

Large overhangs are also needed to keep the rain out. Besides the difficulty of closing windows just before a rain, the relative humidity increases with rain; consequently, windows need to remain open during the rain.

Comfort ventilation is most effective when the indoor temperature



Figure 10.8a The Mayan Indians of the hot and humid Yucatan Peninsula build lightweight, porous buildings for maximum comfort. Note that although mud and rocks are available, experience has led the Mayans to the most comfortable construction method.

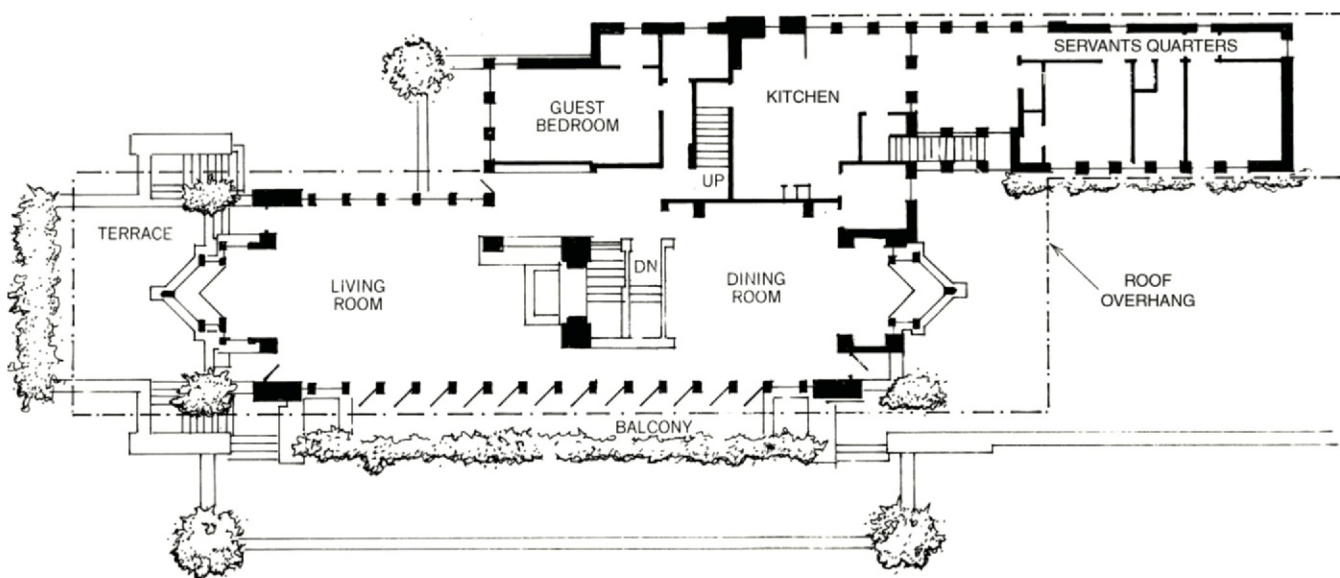


Figure 10.8b Frank Lloyd Wright's Robie House (1909) in Chicago has whole walls of doors and windows that open for cross ventilation. It also has large roof overhangs to keep out the sun and rain.

and humidity are above the outdoor level. This is often the case because of internal heat sources and the heating effect of the sun. Thus, in such cases comfort ventilation not only brings in cooler air but also produces thermal comfort from the resultant air motion. However, when it is much hotter and/or more humid outdoors than indoors, the windows should be closed to avoid excessive heating or humidification of the building. Ceiling or table fans can then be used to move air across people.

Rules for Comfort Ventilation in Hot and Very Humid Climates

1. See Figure 4.12 for the climatic conditions for which comfort ventilation is appropriate.
2. Use fans to supplement the wind.
3. Maximize the airflow across the occupants.
4. Lightweight construction is appropriate only in climates that are very humid, do not require passive solar heating, and use little if any air-conditioning.
5. Use extensive shading and a moderate amount of insulation to keep the MRT near the air temperature.
6. Operable window area should be at least 20 percent of the floor area, split about equally between windward and leeward walls. Much larger window areas can be used in tropical climates.
7. Windows are usually open both during the day and during the night.

10.9 NIGHT-FLUSH COOLING

In all but the most humid climates, the night air is significantly cooler than the daytime air. This cool night air can be used to flush out the heat from a building's mass. The precooled mass can then act as a heat sink during the following day by absorbing heat. Since the ventilation removes the heat from the mass of the building at night, this time-tested passive technique is called **night-flush cooling**.

This cooling strategy works best in hot and dry climates because of the large diurnal (daily) temperature ranges found there—above 30°F (17°C). A large temperature range implies cool nighttime temperatures of about 70°F (21°C) even though daytime temperatures are quite high—about 100°F (38°C). However, good results are also possible in somewhat humid climates, which have only modest diurnal temperature ranges—about 20°F (11°C). The map of the United States in Figure 5.6c illustrates that most of the country, including the humid East, has diurnal temperature ranges of more than 20°F (11°C). The daily ranges are smaller only very close to the coast. Figure 10.9a illustrates how the passive cooling strategies of comfort ventilation and night-flush cooling are related to the typical diurnal temperature range of a climate.

Night-flush cooling works in two stages. At night, natural ventilation or fans bring cool outdoor air into the building to make contact with and cool the indoor mass (Fig. 10.9b). The next morning, the windows are closed to prevent heating the building with hot outdoor air (Fig. 10.9c). The mass now acts as a heat sink and thus keeps the indoor air temperature from rising as fast and far as it would otherwise. However, when the indoor air temperature has risen above the comfort zone, internal circulating fans are required to maintain comfort for additional hours. As with passive heating, a significant temperature range indoors will result. Although more thermal mass will reduce the swing, it is advantageous to allow night flushing to cool the building below the comfort zone in preparation for the hot day to follow.

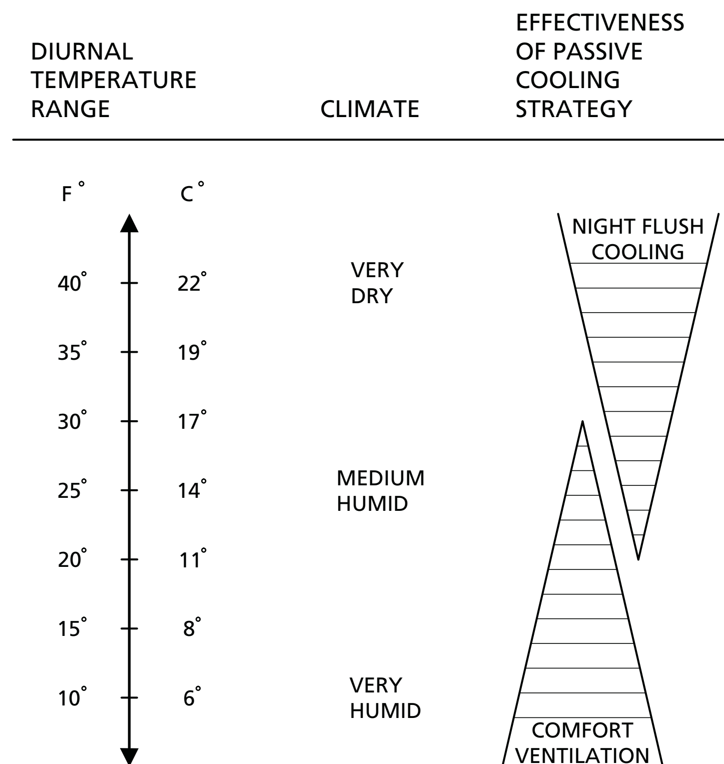


Figure 10.9a The performance of night-flush cooling and comfort ventilation is a function of how dry or humid the climate is, which is indicated by the diurnal temperature range.

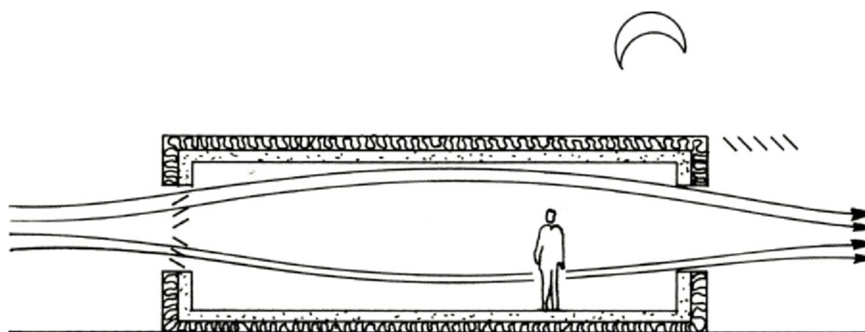


Figure 10.9b With night-flush cooling, night ventilation cools the mass of the building.

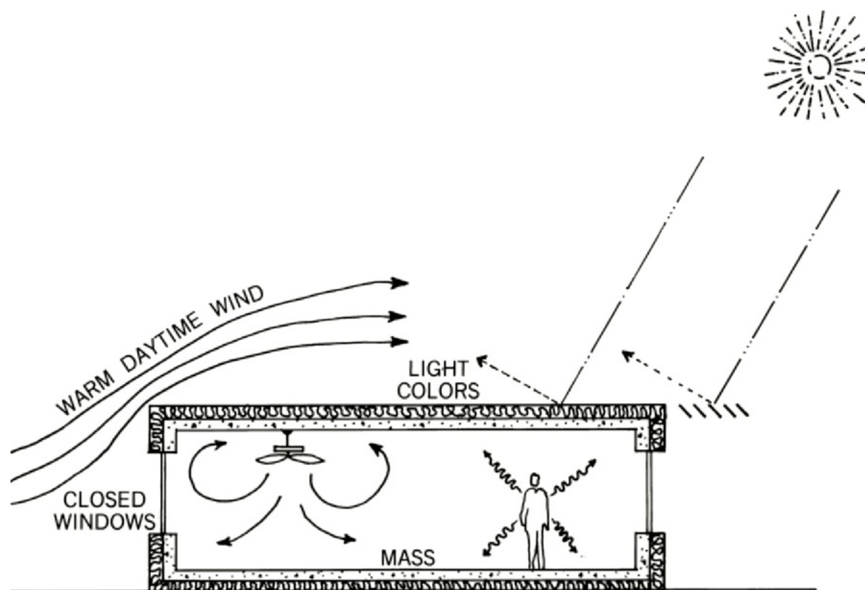


Figure 10.9c During the day, the night-flush cooled mass acts as a heat sink. Light colors, insulation, shading, and closed windows keep the heat gain to a minimum. Interior circulating fans can be used for additional comfort.

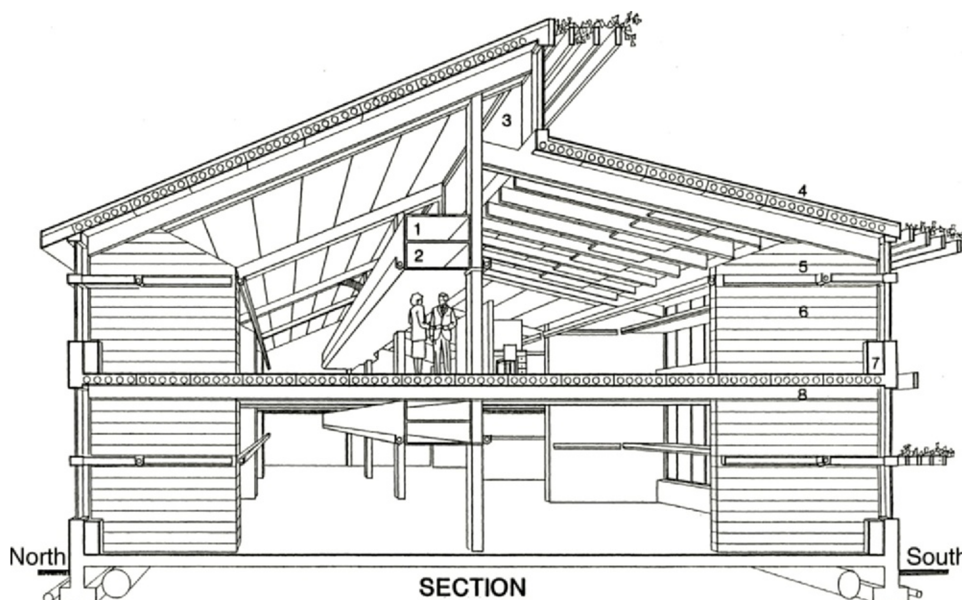


Figure 10.9d This perspective section is of the Emerald People's Utility District Headquarters near Eugene, Oregon. 1, Night-flush cooling; 2, conditioned air supply; 3, clerestory windows; 4, core-slab roof; 5, indoor light shelves; 6, fin walls; 7, conditioned air return; 8, core-slab floor. (Courtesy of WEGROUP PC Architects and Planners, solar strategies by John Reynolds Equinox Design Inc.)

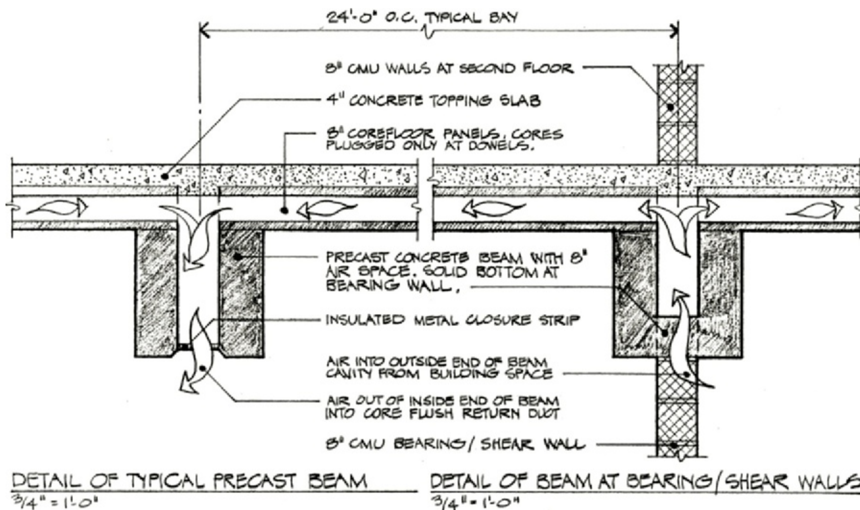


Figure 10.9e This detail shows the airflow through the concrete core-slabs for night-flush cooling. (Courtesy of WEGROUP PC Architects and Planners, solar strategies by John Reynolds Equinox Design Inc.)



Figure 10.9f The dark circles next to the clerestory windows are exhaust fans for night-flush cooling of the Bateson office building in Sacramento, California. The exposed concrete structure is cooled at night to act as a heat sink the following day. Under the large atrium floor is a rock bed, which is also cooled with night air and then used to cool the supply air during the day.

The thermal mass is critical, because without it there is no heat sink to cool the building during the day. The requirements for the mass are similar to those for passive solar heating, and, of course, the mass can serve both purposes. Ideally, the mass should equal 80 lb per square foot (390 kg/m^2) of floor area (concrete weighs about 150 lb/ft^3 (2400 kg/m^3). The surface area of the mass should be more than two times the floor area.

Minimize the heat gain to minimize the amount of mass required. Use heat-avoidance techniques, such as well-shaded windows, a heavily insulated envelope, and light colors. These and many other heat-avoidance techniques are mentioned throughout this book.

To flush out the heat at night, the operable window area should be about 10 to 15 percent of the floor area. When natural ventilation is not sufficient, exhaust fans should be used. With night-flush cooling, the airflow should be directed over the mass, not over the occupants.

In normal buildings, it is difficult to completely flush the mass of its heat at night. A more sophisticated version of night-flush cooling passes the night air through channels in the structural mass. The Emerald PUD Building in Eugene, Oregon, uses night-flush cooling as a major design strategy. Cool night air is passed through a hollow-core concrete floor and roof planks (Figs. 10.9d and 10.9e.)

The Bateson office building in Sacramento, California, uses two different night-flush cooling techniques. Night air cools both the exposed interior concrete structure for direct cooling and a rock bed for indirect cooling (Fig. 10.9f). Cool night air not only blows across the building structure and fabric but also through a large bin located under the atrium floor that is filled with round rocks arranged so that air can flow through them. The Research Support Facility building at NREL uses a concrete labyrinth instead of rocks to store the cool night air in the summer as well as solar-heated air in the winter (see Fig. 8.24c).

Rules for Night-Flush Cooling

1. Night-flush cooling works best in hot and dry climates with a daily temperature range that exceeds 30°F (17°C) but is still effective in somewhat humid regions as long as the daily range is above 20°F (11°C).
2. Except for areas with consistent night winds, window or whole-house fans should be used to flush out the building at night. Ceiling or other circulating indoor fans should be used during the day when the windows are closed.
3. Ideally, there should be about 80 lb of mass for each square foot (390 kg/m^2) of floor area, and the surface area of this mass should be more than two times the floor area. The mass has to be on the indoor side of the insulation.

4. The airflow at night must be directed over the mass to ensure good heat transfer.
5. The window area should be between 10 and 15 percent of the floor area.
6. Windows should be open at night and closed during the day.

Before we look at other passive cooling strategies, it is worthwhile to note that natural ventilation is by far the most common passive cooling technique. It can save much energy, provide better indoor air quality, and increase occupant satisfaction. Since people desire to control their immediate environment, operable windows are very popular. To prevent conflict with the air-conditioning system, the architect and engineer need to cooperate at all stages of the design process. For example, switches can be placed on windows that will prevent the mechanical system from operating if the windows are open. Or, the windows could be mechanically operated by the building energy management system, which also controls the air-conditioning system.

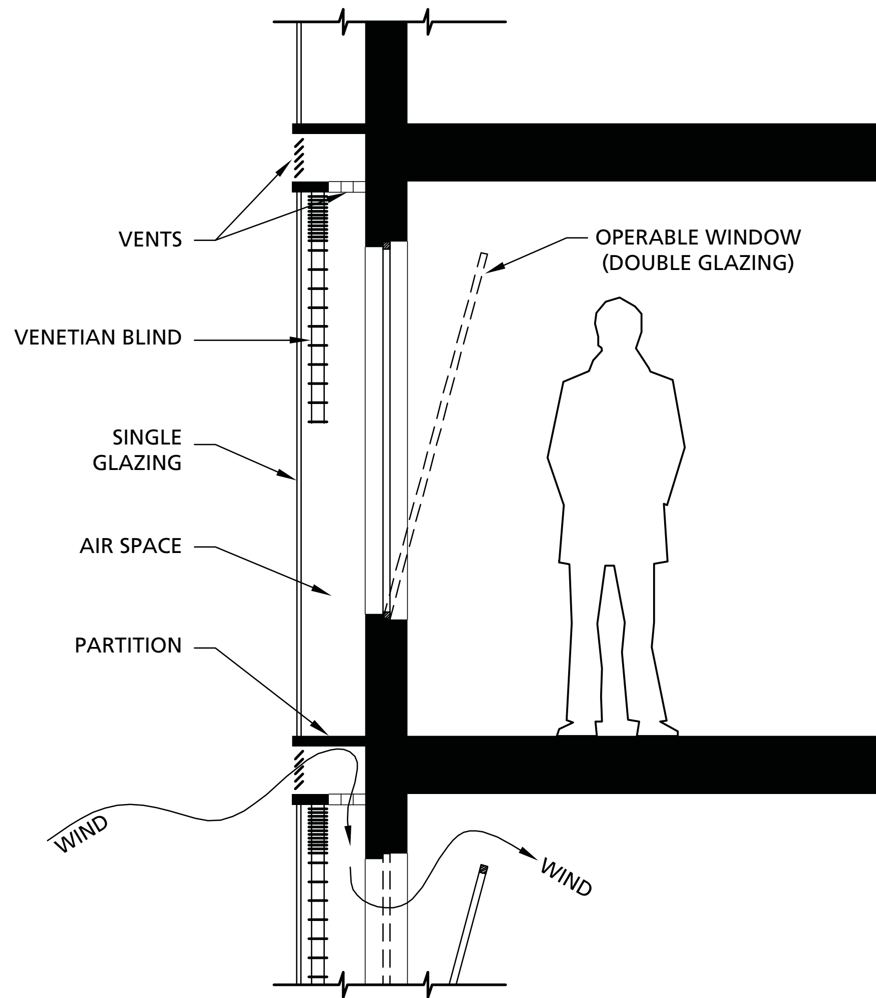


Figure 10.10a Double-skin facades are dynamic in that they control natural ventilation, shading, passive solar, and daylighting, all of which change with time.

10.10 DOUBLE-SKIN FACADES AND OPERABLE ROOFS

Double-skin facades, which are also known as smart facades, have many functions and are usually dynamic, unlike most curtain walls. They can save energy and increase comfort by integrating all of the following strategies: passive solar, shading, daylighting, increased thermal resistance, and natural ventilation. Double-skin facades usually have a double-glazed window, an air space between 6 and 30 in. (15 and 75 cm) deep, and a layer of safety or laminated glass on the outside (Fig. 10.10a). The air space is usually divided into vertical and horizontal compartments to control the spread of fire and noise and to prevent the stack effect from transferring hot, stale air from lower floors to upper floors.

Most smart facades are dynamic by means of venetian blinds and operable windows. The shading and daylighting benefits of the blinds are described in Chapters 9 and 13. The operable windows provide ventilation for both quality indoor air (Chapter 16) and passive cooling, which is discussed here. Smart facades can support both comfort ventilation and night-flush cooling in a more controlled manner than windows, because they prevent the entry of rain, control noise, and prevent excessively high airspeeds even on the fiftieth floor on a windy day. One of the most famous smart facades is found on the Commerzbank (Fig. 10.10b). The author believes that double-skin facades are most appropriate in high-rise buildings with operable windows and exterior shading systems.

Certain building types can use smart roofs that retract when not needed. Baseball stadiums are the best examples, but enclosed swimming pools are the most common application. Movable roofs are also used for playgrounds, zoos, greenhouses, atriums, and pedestrian streets. Pre-engineered systems make movable roofs an economical solution for reducing cooling loads where glass roofs are desired. Of course, they also create delight. (Fig. 10.10c).

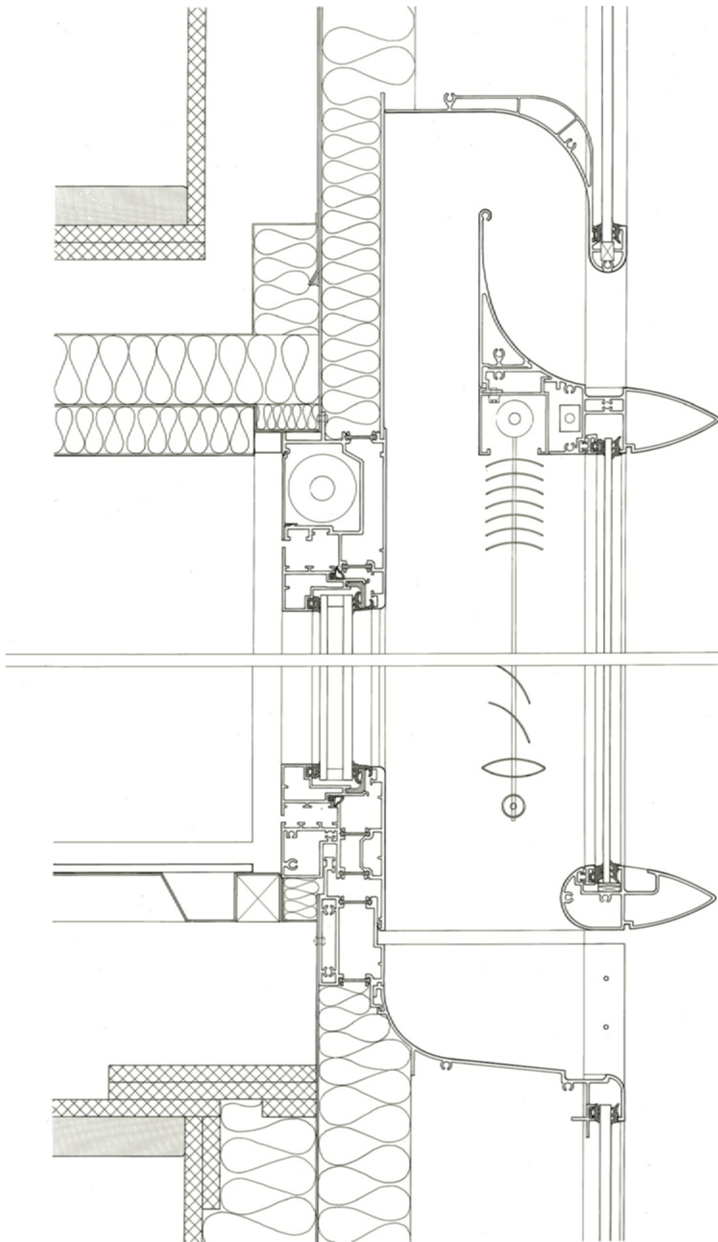


Figure 10.10b A detail for the double-skin facade of the Commerzbank, Frankfurt, Germany, is shown. (Courtesy of Foster and Partners)



Figure 10.10c Many spaces, such as this Best Western Lamplighter Inn, London, Ontario, benefit from having the roof open up on hot days. (Project by Open Aire Inc., www.openaire.com)

In hot and dry climates, traditional buildings used deep courtyards and narrow alleys to expose the massive walls to only a few hours of direct sunlight. However, all of the walls radiated to the cold night sky all night long. Thus, the walls were quite cool by morning. As mentioned in Chapter 9, shading the courtyards and narrow streets during the day provided even more comfort.

Because the roof has the greatest exposure to the sky, it is the best location for a long-wave radiator. Since only shiny metal surfaces are poor emitters, any other surface will be a good choice for a long-wave radiator. Painted metal (any color) is especially good because the metal conducts heat quickly to the painted surface, which then readily emits the energy. Such a radiator on a clear night will cool as much as 12°F (7°C) below the cool night air. On humid nights, radiant cooling is less efficient, but a temperature depression of about 7°F (4°C) is still possible. Clouds, on the other hand, almost completely block the radiant cooling effect (Fig. 10.11b).

10.11 RADIANT COOLING

As was explained in Chapter 3, all objects emit and absorb radiant energy, and an object will cool by radiation if the net flow is outward. At night the long-wave infrared radiation from a clear sky (outer space) is much less than the long-wave infrared radiation emitted from a building, and thus there is a net flow to the sky (Fig. 10.11a).

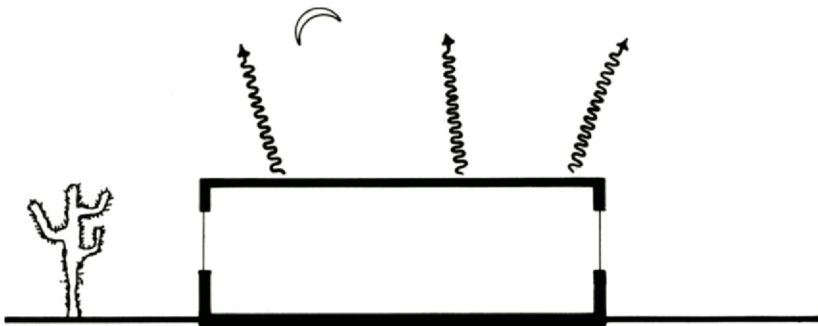


Figure 10.11a On clear nights with little humidity, there is strong radiant cooling to the cold night sky (outer space).

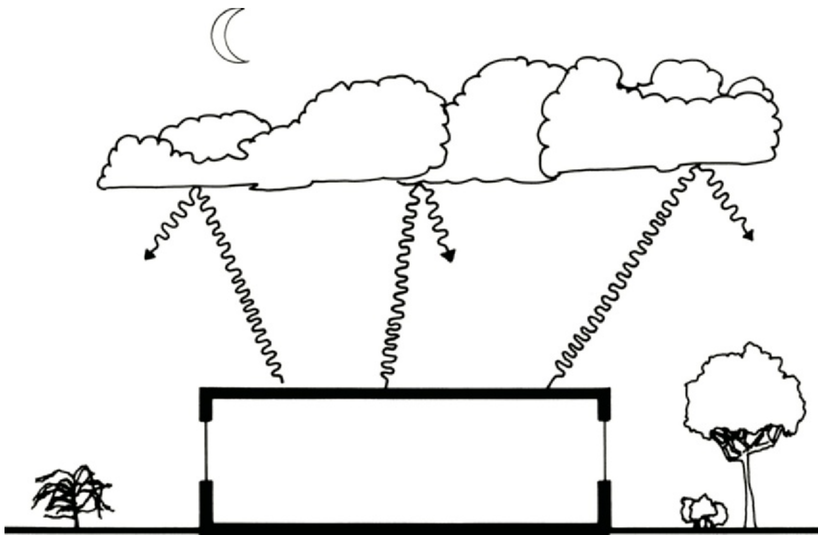


Figure 10.11b Humidity reduces radiant cooling, and clouds practically stop it.

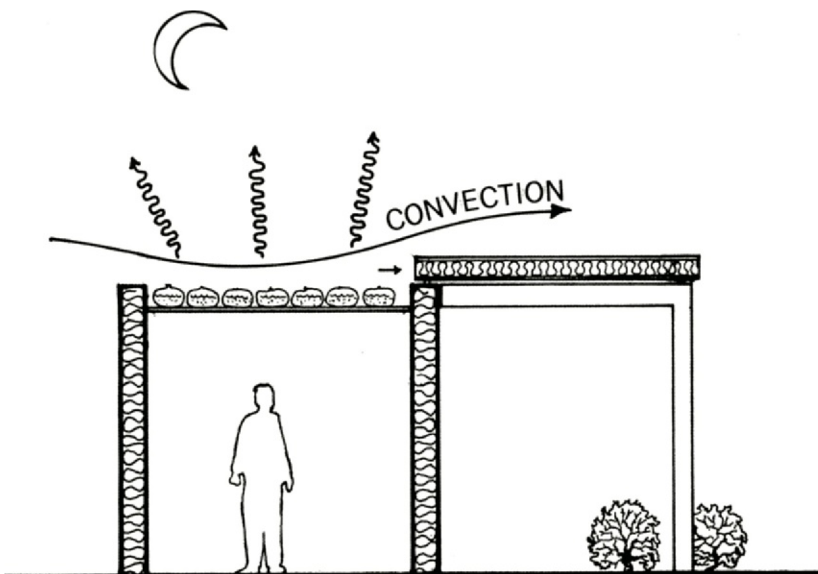


Figure 10.11c During a summer night, the insulation is removed and the bags of water are allowed to give up their heat by radiant cooling.

Direct Radiant Cooling

Potentially the most efficient approach to radiant cooling is to make the roof itself the radiator. For example, an exposed-concrete roof will rapidly lose heat by radiating to the night sky. The next day, the cool mass of concrete can effectively cool a building by acting as a heat sink. The roof, however, must then be protected from the heat of the sun and hot air. Consequently, insulation must be added to the roof every morning and removed every evening.

Harold Hay has designed and built several buildings using this concept, except that he used plastic bags filled with water rather than concrete for the heat-sink material. At night, the water bags are exposed to the night sky by removing the insulation that covered them during the day (Fig. 10.11c). When the sun rises the next day, the water bags are covered by the movable insulation. During the day, the water bags, which are supported by a metal deck, cool the indoors by acting as a heat sink (Fig. 10.11d). Although this "roof pond" concept has been tested and shown to be effective, an inexpensive, reliable, and convenient movable insulation system has still not been achieved.

Another direct-cooling strategy uses a lightweight radiator with movable insulation on the inside. This eliminates two of the problems associated with the above concept: a heavy roof structure and a movable insulation system exposed to the weather. With this system, a painted sheet-metal radiator, which is also the roof, covers movable insulation (Fig. 10.11e). At night, this insulation is in the open position so that heat from the building can migrate up and be emitted from the radiator. For the cooling effect to be useful during the day, sufficient mass must be present in the building to act as a heat sink. Also, during the day, the insulation is moved into the closed position

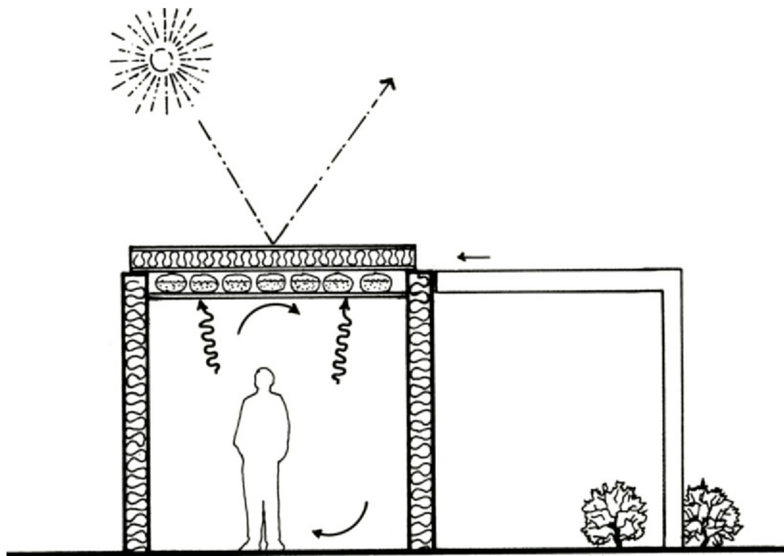


Figure 10.11d During a summer day, the water bags are insulated from the sun and hot outdoor air, while they act as a heat sink for the space below.

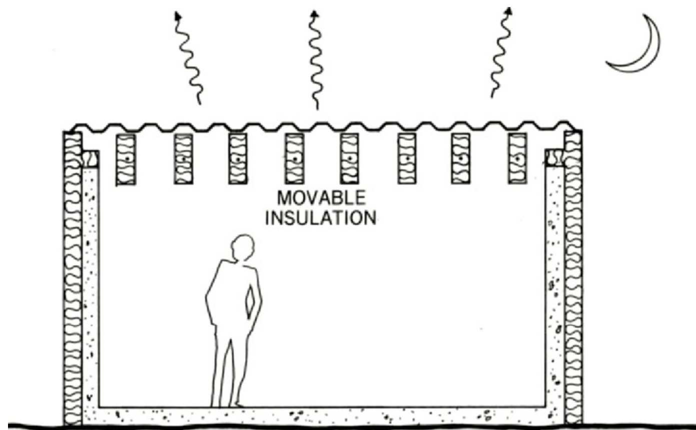


Figure 10.11e At night, the movable insulation is in the open position so that the building's heat can be radiated away. This is an example of direct radiant cooling.

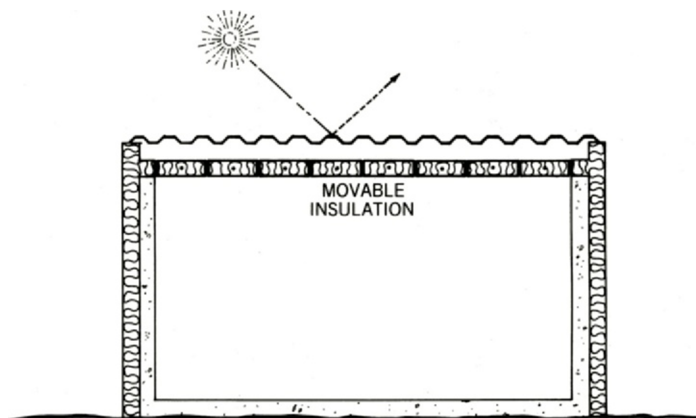


Figure 10.11f During the day, the insulation is in the closed position to keep the heat out. The cool interior mass now acts as a heat sink.

to block the heat gain from the roof (Fig. 10.11f).

Indirect Radiant Cooling

The difficulty with movable insulation suggests the use of specialized radiators that use a heat-transfer fluid. This approach is much like active solar heating in reverse. In Figure 10.11g the painted metal radiator cools air at night, which is then blown into the building to cool the indoor mass. The next morning the fan is turned off, and the building is sealed. The cooled indoor mass now acts as a heat sink. The radiator is vented during the day to reduce the heat load to the building (Fig. 10.11h). Unless the radiator is also used for passive heating, it should be painted white, since that color is a good emitter of long-wave radiation and a poor absorber of short-wave (solar) radiation.

If there is not enough exposed mass in the building, a rock bed can be used. At night, the cooled air is blown through the rock bed to flush out the heat. During the day, indoor air blown across the rock bed is cooled by giving up its heat to the rocks. This is one of the passive cooling techniques used by the Bateson office building (see Fig. 10.9f).

Rules for Radiant Cooling

1. Radiant cooling will not work well in very cloudy regions. It performs best under clear skies and low humidity, but will still work at lower efficiency in temperate regions.
2. This cooling concept applies mainly to one-story buildings.
3. Unless the radiator is also used for passive heating, the radiator should be painted white.
4. Since the cooling effect is small, the whole roof area should be used.
5. Thermal mass is needed to act as a heat sink during the day.

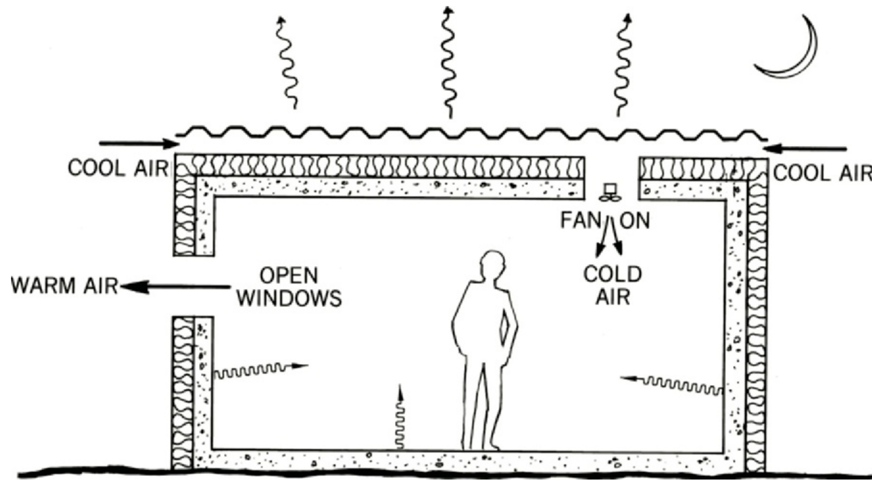


Figure 10.11g The specialized radiator cools air, which is then blown into the building to cool the thermal mass. This is an example of indirect radiant cooling.

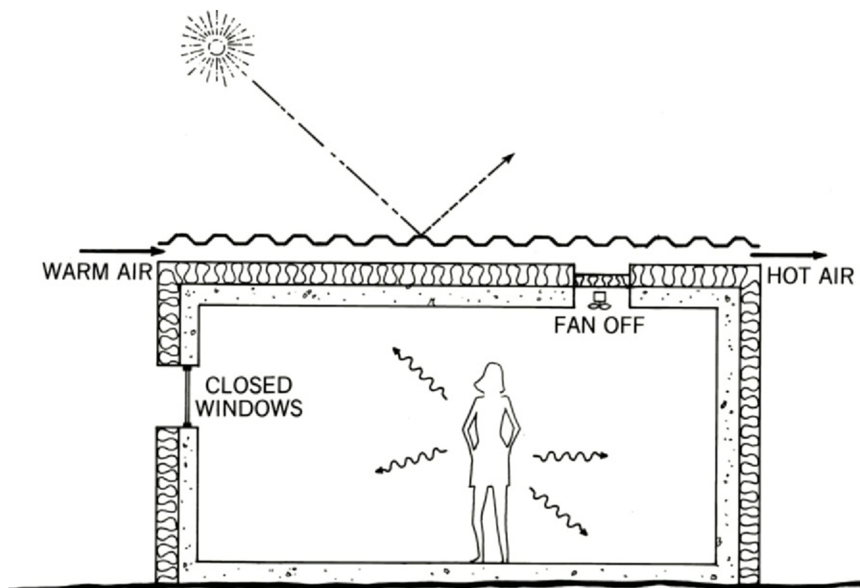


Figure 10.11h During the day, the radiator is vented outdoors, while the building is sealed and the cooled mass acts as a heat sink.

10.12 EVAPORATIVE COOLING

When water evaporates, it draws a large amount of sensible heat from its surroundings and converts this heat into latent heat in the form of water vapor. As sensible heat is converted to latent heat, the temperature drops. This phenomenon is used to cool buildings in two very different ways. If the water evaporates in the building or in the fresh-air intake, the air will be not only cooled but also humidified. This method is called direct evaporative cooling. If, however, the building or indoor air is cooled by evaporation without humidifying the indoor air, the method is called indirect evaporative cooling.

Evaporative cooling is much less energy intensive than conventional cooling, with energy savings of 30 to 90 percent. The required equipment is also much less expensive. Another environmental benefit is that no CFCs are used. The water usage of 3 to 11 gal (11 to 42 liters) per day for a house is not a serious problem in most areas. Since modern water closets use 1.6 gallons per flush (6 lpf), the coolers use the equivalent of two to seven flushes per day. The main drawback to evaporative cooling is that its use is limited to dry climates.

Direct Evaporative Cooling

When water evaporates in the indoor air, the temperature drops but the humidity goes up. In hot and dry climates, the increase in humidity actually improves comfort. However, direct evaporative cooling is not appropriate in humid climates because the cooling effect is low and the humidity is already too high. See Figure 4.12 for the kind of climate that supports direct evaporative cooling. On the map of the United States in Figure 5.6c, direct evaporative cooling is effective for all regions with a daily temperature range above 30°F (17°C) and partially effective in regions with

a daily temperature range of 25° to 29°F (14° to 16°C). Horticultural greenhouses are an exception because most plants thrive on high humidity but not high temperature.

The most popular form of direct evaporative cooling is accomplished with commercially available evaporative coolers (swamp coolers). Although they look like active mechanical devices from the outside, they are actually quite simple and use little energy (Figs. 10.12a and 10.12b). A fan is used to bring outdoor air into the building by way of a wet screen. A modest amount of water is required to keep the screen wet. To maintain comfort, a high rate of ventilation is required during the day (about twenty air changes per hour).

Misting the air has become a popular direct evaporative-cooling strategy in all hot climates but works best in dry climates. Water under high pressure is atomized into tiny droplets, which then readily evaporate to cool the air.

Misting is mainly used to cool outdoor spaces. Unfortunately, if the area is too sunny or too windy, the benefit of misting will be minimal. However, the cooling effect can be significant in sheltered outdoor spaces and greenhouses. Misting is often used more for the atmosphere it creates than for its cooling benefits.

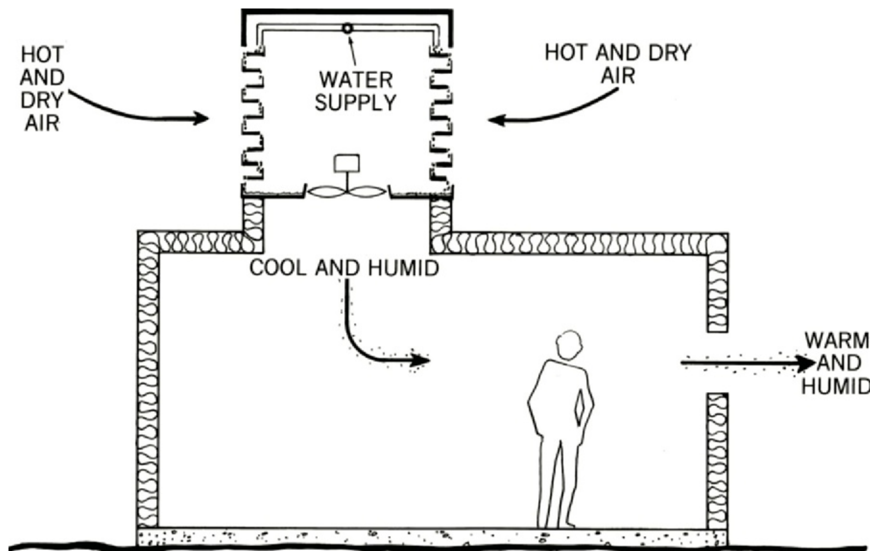


Figure 10.12a Evaporative coolers (swamp coolers) look a great deal like central air-conditioning units, but their cooling mechanism is very simple and inexpensive. They are appropriate only in dry climates.



Figure 10.12b Evaporative coolers are widely used in hot and dry regions. This is an example of a direct evaporative cooler on the roof of a house.

Indirect Evaporative Cooling

The cooling effect from evaporation can also be used to cool the roof of a building, which then becomes a heat sink to cool the interior. This technique is an example of indirect evaporative cooling, and its main advantage is that the indoor air is cooled without increasing its humidity.

A critical aspect of evaporative cooling is that the heat of vaporization must come from what is to be cooled. Thus, spraying a sunlit roof is not especially good because the heat of the sun will evaporate most of the water. On the other hand, the heat to evaporate water at night or from a shaded roof pond comes mainly from the building itself.

Figure 10.12c illustrates the basic features of roof-pond cooling. An insulated roof shades the pond from the sun. Openings in the roof enable air currents to pass over the pond during the summer. As water evaporates, the pond will become cooler and, together with the ceiling structure, will act as a heat sink for the interior of the building. During the winter, the pond is drained and the roof openings are closed. The main disadvantage of this system is the cost of the concrete or metal ceiling and waterproofing.

A clever alternative to the above roof pond is the roof pond with floating insulation (Fig. 10.12d). At night, a pump sprays the water over the top of the insulation, and it cools by both evaporation and radiation. When the sun rises, the pump stops and the water remains under the insulation, where it is protected from the heat of the day. Meanwhile, the water, together with the roof structure, acts as a heat sink for the interior. Although the cooling occurs only at night, it is very effective because of the combined action of evaporation and radiation.

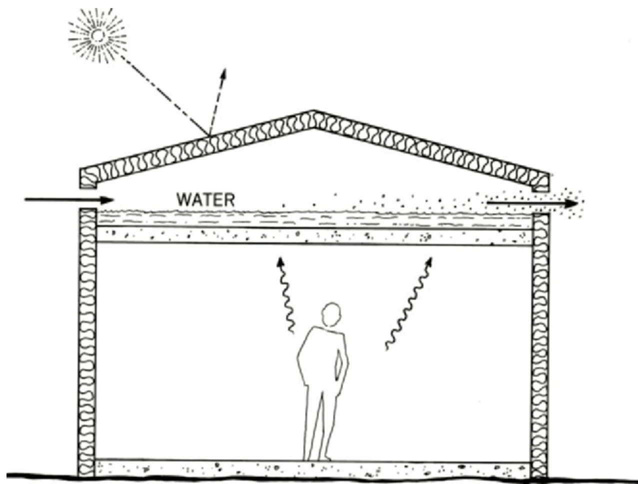


Figure 10.12c This indirect evaporative-cooling system uses a roof pond. Note that no humidity is added to the indoors.

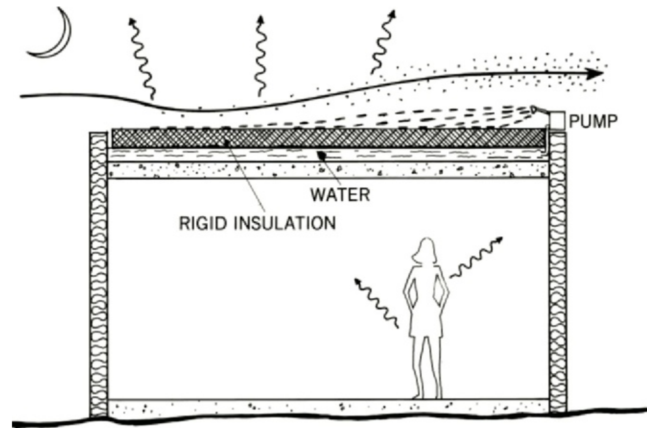


Figure 10.12d This nighttime indirect evaporative-cooling system uses floating insulation to protect the water from the sun and heat of the day.

A more conventional version of the water spray design is to store the cooled water in a tank and to precool the floor slab at night (Fig. 10.12e). At night the water is sprayed on a conventional roof, where it is cooled by both evaporation and radiation to the night sky. The cooled water is then pumped through tubing embedded in the floor slab and stored in a tank for the next day. Of course, the tubing in the floor slab can also be used for radiant heating in the winter. The cooled water stored in the tank can be used with fan-coil units the next day (see Figs. 16.14r–16.14t).

Indirect evaporative coolers are now commercially available as packaged units. They are similar to the evaporative coolers mentioned above except that they do not humidify the indoor air (Fig. 10.12f). Outdoor air is used to evaporate water off the surface of tubes. The necessary heat of vaporization is drawn in part from these tubes, through which indoor air is flowing. Thus, indoor air is cooled but not humidified. These units are sometimes used in series with evaporative coolers for extra cooling with less humidification.

Recently a much more efficient type of indirect evaporative cooler has been developed based on a newly discovered thermodynamic cycle called the M-cycle. The patented Coolerado

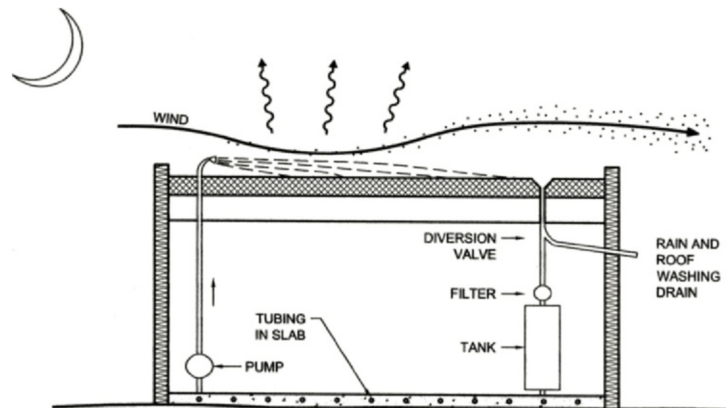


Figure 10.12e Water that is cooled by both evaporation and radiation to the night sky is used to cool the floor slab to create a heat sink for the next day. Additional water can be cooled and stored in tanks for use in fan-coil units the next day.

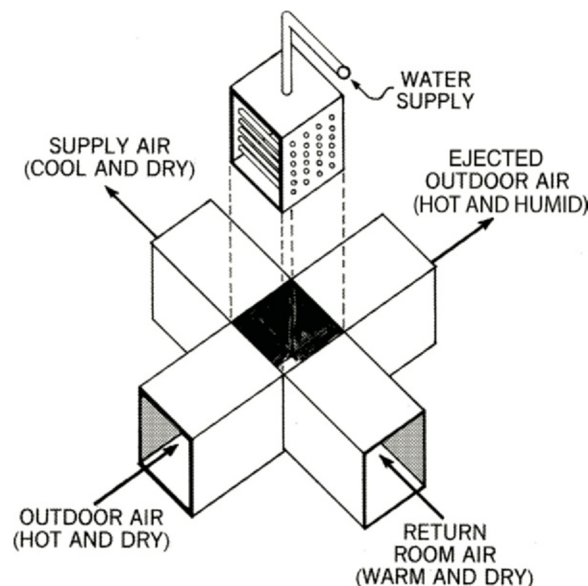


Figure 10.12f Indirect evaporative coolers reduce the indoor air temperature without increasing its humidity.

system is a heat and mass exchanger (HMX) that cools and dehumidifies air better than conventional indirect evaporative coolers.

Indirect evaporative cooling has two advantages over direct evaporative cooling: the indoor air is not humidified, and it can be used in climates too humid for direct evaporative cooling. Thus, the climates that have a daily range of 25° to 29°F (14° to 16°C), which is marginal for direct evaporative cooling, can be effectively cooled by indirect evaporative coolers. Figure 5.6c shows these climates to be a significant part of the United States.

Rules for Evaporative Cooling

1. Direct evaporative cooling is appropriate only in dry climates.
2. Indirect evaporative cooling works best in dry climates but can also be used in somewhat humid climates because it does not add to the indoor humidity.
3. A combination of direct and indirect is sometimes the best choice.

Because vegetated roofs (green roofs) cool the roof and not the indoors, they are a heat avoidance strategy rather than a passive cooling strategy. Because they are also most appropriate in cities, they are discussed in Section 11.10.

10.13 COOL TOWERS

Cool towers are passive evaporative coolers that act like reverse chimneys (Fig. 10.13a). At the top of the tower, water is sprayed on absorbent pads. As air enters the top of the tower, it is cooled, becomes denser, and sinks. The cool air then enters the building through openings that look much like fireplaces. Thus, instead of hot air flowing up, cool air flows down inside the cool towers, filling the building with cool air without the help of fans.

Cool towers have been working successfully at the Zion National Park Visitor Center in Utah since the year 2000 (Fig. 10.13b). The buildings also use natural ventilation as much as possible, with the cool towers reserved for the hottest weather. In addition, the buildings use many other energy-responsive strategies to achieve 70 percent annual energy savings compared to similar conventional buildings. (For the passive heating strategies used, see Figure 7.9e.) The performance of a cooling tower can be improved by coupling it with a solar chimney.

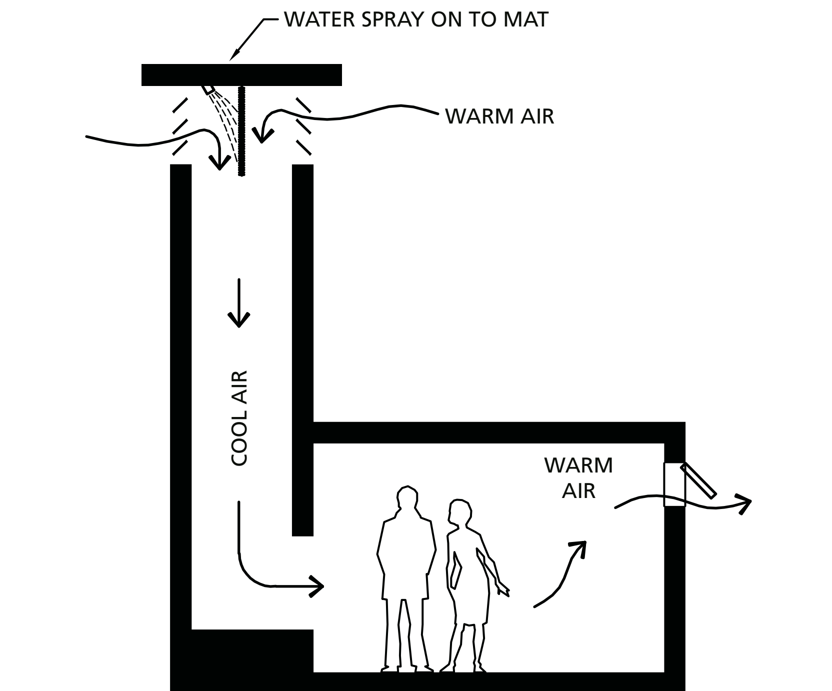


Figure 10.13a In cool towers, air is cooled by evaporation, which then sinks to fill the building with cool air.



Figure 10.13b The Zion National Park Visitor Center in Utah is kept comfortable in the hot and dry summer by means of cool towers.

10.14 EARTH COOLING

Before earth-cooling techniques can be discussed, the thermal properties of soil must be considered. Earth, especially wet earth, is both a good conductor and storer of heat (i.e., it has high heat capacity). The temperature at the earth's surface is the result of solar gain, radiant loss, and heat conduction to or from lower layers of the ground. Since air is heated mainly by its contact with the earth, the surface soil temperature is about the same as the air temperature with its large annual fluctuations. However, because of the large time lag of heating and cooling the earth, the soil temperature fluctuates less and less as the soil depth increases. At about 20 ft (6 m) in depth, the summer/winter fluctuations have almost disappeared and a year-round steady-state temperature exists, which is equal to the average annual air temperature.

The graph of Figure 10.14a shows the earth temperatures as a function of depth. One curve represents the maximum summer temperatures, and the other represents the minimum winter temperatures of the soil. The ground temperatures at any depth fluctuate left and right between these curves during a year.

Since the ground temperature is always below the maximum air temperature, the deep earth can always be used as a heat sink in the summer. However, unless the temperature difference is great enough, earth cooling is not practical. The map in Figure 10.14b shows that the deep soil temperatures are low enough for earth cooling (approx. 60°F [15°C] or less) in much of the country. Even if the soil is too warm for actual cooling, it will, nevertheless, be much cooler than the outdoor air. Earth sheltering, which is described in Section 15.12, can be very advantageous in some climates.

Deep earth temperatures are equal to the mean annual air temperature of a location (e.g., 77°F (30°C) in southern Florida and 42°F (5°C) in North Dakota).

Direct Earth Coupling

When earth-sheltered buildings have their walls in direct contact with the ground (i.e., there is little or no insulation in the walls), we say that there is direct earth coupling. In regions

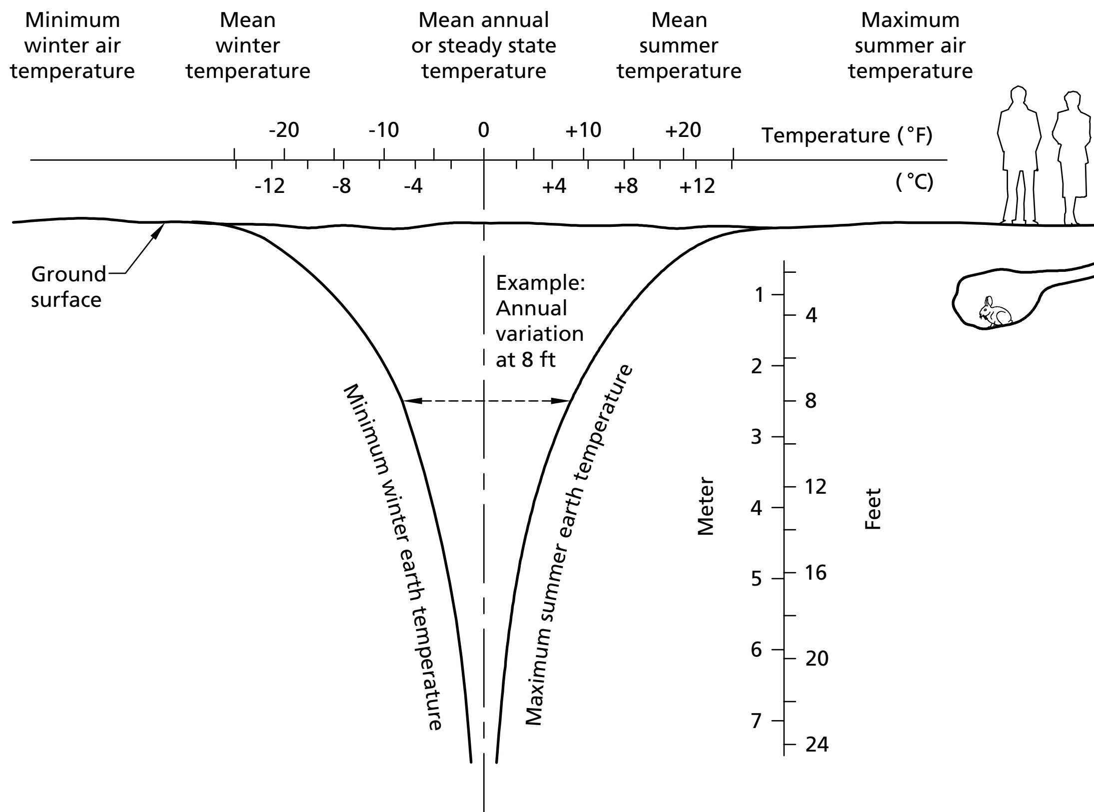


Figure 10.14a Soil temperature varies with time of year and depth below grade. To find the maximum or minimum soil temperature at any depth, first find the mean annual steady-state temperature from Figure 10.14b and then, according to depth, add (summer) or subtract (winter) the deviation from the centerline.

where the mean annual temperature is below 60°F, (15°C) direct coupling will be a significant source of cooling. This asset becomes a liability, however, in the winter, when excess heat will be lost to the cold ground. One solution is to insulate the earth around the building from the cold winter air but not from the building (Fig. 10.14c). This horizontal insulation buried in the ground will bring the steady-state temperature closer to the surface and closer to the building. In much of the United States, it would be an advantage to have a building surrounded by the local steady-state (i.e., deep-earth) temperature.

Indirect Earth Coupling

A building can be indirectly coupled to the earth by means of earth tubes. When cooling is desired, air is drawn through the tubes into the building (Fig. 10.14d). The earth acts as a heat sink to cool the air.

To get the maximum cooling effect, the tubes should be buried as deeply as possible to take advantage of that constant, deep-earth temperature, which is the coolest available in the summer. Deep below the surface, the soil is also more likely to be moist during the summer. Since wet soil has much higher conductivity than dry soil, there is more heat transfer per foot of tubing. Nevertheless, very long pipes are needed to cool a building.

The open-loop system shown in Figure 10.14d provides pre-conditioned ventilation air, which is cooled in the summer and warmed in the winter.

The greatest problem with earth tubes is condensation, which occurs mainly in humid climates where the earth temperature is frequently below the dew point, or saturation temperature, of the air. The tubes, therefore, must be sloped for water to drain into a sump for removal.

Because of the potential for mold growth in the wet tubes, provision must be made to both inspect and clean them. The diameter of the earth tubes can vary greatly, with some large enough for a human to enter. Tubes must be absolutely tight to prevent radon gas or water from entering. (Radon is discussed further in Section 15.15.)

The earth can be cooled in the summer to increase the performance of the earth tubes. Since the soil is heated mostly by sunlight, shading from trees is very beneficial (Fig. 10.14e). The soil can also be cooled

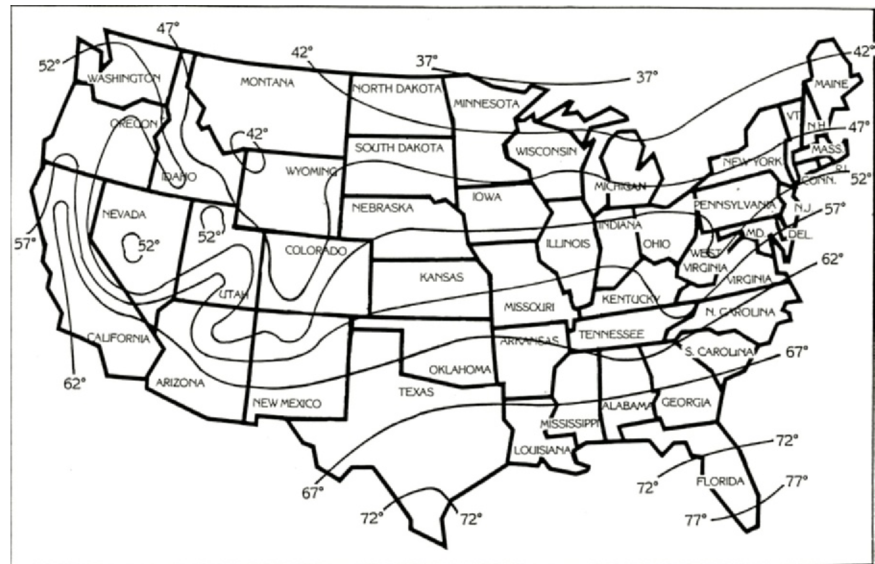


Figure 10.14b Deep-earth temperatures are approximately equal to these well-water temperatures. (Reprinted with permission of National Water Well Association.)

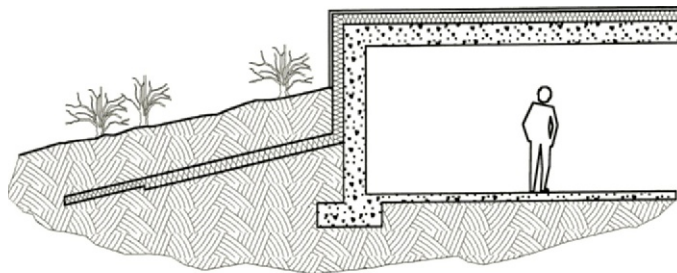


Figure 10.14c Insulating the soil around an earth-sheltered building creates a more desirable earth temperature for the building in both summer and winter. The soil will be warmer in the winter and cooler in the summer.

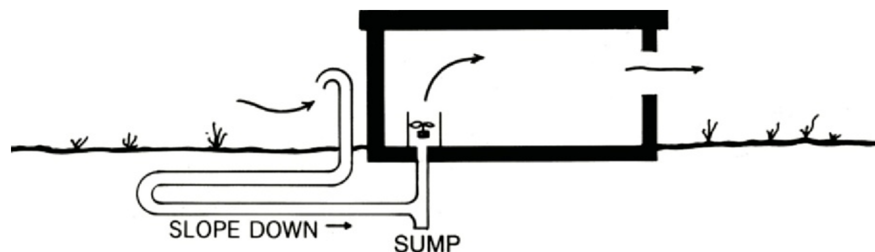


Figure 10.14d Indirect earth cooling is possible by means of tubes buried in the ground. Sloped tubes and a sump are required to catch condensation. An open-loop system is shown, while a closed-loop system would return the air from indoors.

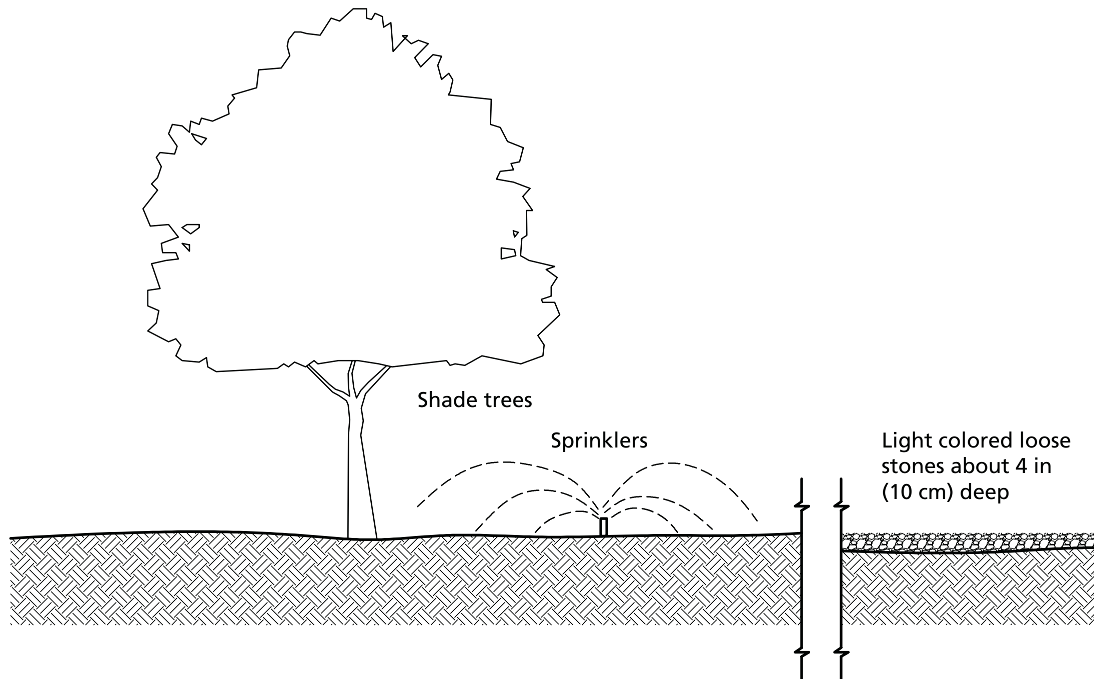


Figure 10.14e Soil can be cooled significantly below its natural summer temperature by shading it and by keeping it wet for evaporative cooling. However, it is best to wet the soil at night. The cooled soil will improve the performance of earth tubes in the summer. In very dry regions where shade trees are not an option, a very light-colored cover of loose stones can reflect the sun but still allow evaporation to occur if any water is present in the soil.

by evaporation. However, the evaporation must occur at the level of the soil and not from the transpiration of plants, because the latter cools the air instead of the soil. Furthermore, sprinklers should be used only at night to prevent solar-heated water from percolating into the ground.

In areas too dry to grow shade trees, the ground can be covered with about 4 in. (10 cm) of light-colored stones that reflect most of the sunlight. If the soil has any water content, the water will evaporate with the vapor migrating through the porous stone cover (Fig. 10.14e).

Factors for Earth Cooling Design

1. The steady-state deep-earth temperature is similar to the mean annual temperature at any location (Fig. 10.14b).
2. Directly coupled earth cooling works well when the steady-state earth temperature is somewhat below 60°F (15°C). If the earth is much colder, it must be insulated to minimize winter heat loss (Fig. 10.14c).
3. Earth tubes are best in dry climates.
4. In humid climates, the condensation on walls or in earth tubes might cause biological activity, which is a health risk.

10.15 DEHUMIDIFICATION WITH A DESICCANT

In humid regions, dehumidifying the air in summer is very desirable for thermal comfort and control of mildew. Two fundamental ways to remove moisture from the air exist. With the first method, the air is cooled below the dew point temperature. Water will then condense out of the air. Conventional air-conditioning and dehumidification use this principle.

The second method involves the use of a **desiccant** (drying agent). A number of chemicals, such as silica gel, natural zeolite, activated alumina, and calcium chloride, will absorb large amounts of water vapor from the air. However, there are two difficulties with the use of these materials. First, when water vapor is absorbed and turned into liquid water, heat is given off. This is the same heat that was required to vaporize the water in the first place (heat of vaporization). Thus, if a desiccant is placed in a room, it will heat the air as it dehumidifies it (i.e., the desiccant converts latent heat into sensible heat). Thermal comfort will, therefore, require another cooling stage to lower the temperature of the air.

The second problem with the use of a desiccant is that the material soon becomes saturated with water and stops dehumidifying. The desiccant must then be **regenerated** by boiling off the water. Presently, desiccant dehumidification is used mainly in the heat exchangers that recover both sensible and latent heat (see Section 16.18). Recently a new type of air conditioner called Advantix was developed which uses desiccant dehumidification as part of the cooling cycle. It thereby achieves a much higher efficiency compared to a conventional air conditioner.

10.16 SOLAR CHIMNEY

A solar chimney can increase the ventilation of a building by increasing the stack effect whenever the sun is shining. It is especially valuable on days when there is no wind augmenting the stack effect. A solar chimney uses the sun to heat air to increase its buoyancy. The air then rises faster, exhausting more warm air and in turn pulling more cool air into a building at lower levels. Solar chimneys come in all sizes and can be used to ventilate everything from outhouses and composting toilets (Fig. 10.16a), to medium-sized buildings, to high-rise buildings.

To maximize the effect, solar chimneys need to be exposed to the summer sun all day long, which is only possible on the roof. A black-painted vertical pipe works quite well (Fig. 10.16a), but as with passive solar heating, much more heat is captured with glass because of the greenhouse effect. Not only will glass-covered chimneys exhaust more air in the summer, but they can also be a source of heat in the winter, when they can act as active solar space heaters (Fig. 10.16b). In a very effective application in Manitoba by Smith Carter Architects and Engineers (Manitoba Hydro Place), dampers close the top of the chimney in winter, and fans pull the warm exhaust air down to recover much of the heat before dumping the air outdoors (Fig. 10.16c).



Figure 10.16a Solar chimneys can be used to prevent odors in outhouses and composting toilets. The solar chimney exhausts air from the sanitary holding tank so that the air flows into rather than out of the toilet seat. The outhouse shown is in a remote national forest camp ground that has neither flowing water nor electricity. The author's nose can vouch for the effectiveness of the solar chimney.



Figure 10.16b To maximize the stack effect, the solar chimneys at the Sidwell Friends School use a large surface structure with some glass for the greenhouse effect. Because vertical surfaces receive little sunshine around 12 noon, the glass is slanted. Courtesy of Halkin Mason Photography.



Figure 10.16c The solar chimney at the Manitoba Hydro Place is the whole height of the building plus several stories. The chimney exhausts air from all of the office floors, and the amount of airflow is controlled by dampers operated by the buildings management system (i.e., computer). The glass-covered chimney is on the south side of the building to maximize both summer and winter solar collection. In the summer, the warm exhaust air exits the openings at the top, while in the winter the warm air is pulled down to recover its heat. Some thermal mass is located inside the top of the chimney to continue the stack effect for some time after the sun has set. Photograph by Edward Hueber, Manitoba Hydro Place, September 2009, Smith Carter Architects and Engineers Inc.

To prevent a solar chimney from heating the building, it must be located outside the thermal envelope. Consequently, free-standing solar chimneys work best, and if they rest on or against a building, insulation must isolate them. Even with a solar chimney, the stack effect is weak, so the inlet and outlet openings should be as large as possible, the airpath should be as unobstructed as possible, and the area exposed to the sun as large as possible.

10.17 CONCLUSION

Passive cooling strategies have the greatest potential in hot and dry climates. Just about every cooling technique will work there. In very humid regions, only comfort ventilation will be very helpful. However, many regions that are considered hot and humid are humid for only part of the overheated period. There are often many months that are hot but not humid. In such regions, night-flush cooling and night-radiation cooling can be beneficial. Most of the eastern United States has this moderately humid climate, where a mix of various passive cooling strategies can replace or reduce the need for air-conditioning during much of the summer. However, in every climate, the first and best strategy for summer comfort is heat avoidance.

KEY IDEAS OF CHAPTER 10

1. Make full use of heat avoidance before applying any passive cooling strategies.
2. Comfort ventilation is used day and night to cool people and to keep the indoor temperature close to the outdoor temperature. This type of ventilation is used mainly in very humid climates and in temperate climates when the humidity is high.
3. Night-flush cooling uses night ventilation to cool the mass of the building. During the day, the windows are closed, and the mass acts as a heat sink. This passive cooling strategy is used in both dry climates and temperate climates whenever the humidity is low.
4. Air flows from positive- to negative-pressure areas.
5. There is a positive pressure on the windward side, and a negative pressure on both the leeward side and the sides of the building parallel to the wind.
6. Hot air can be exhausted from the top of a building by stratification, the stack effect, the shape of the roof (the venturi effect), and the increased wind velocity found at higher elevations (the Bernoulli effect).
7. Use cross ventilation whenever possible.
8. Have air flow across people for comfort ventilation and across the building mass for night-flush cooling.
9. Radiant cooling from the roof works well in climates in which the humidity is low and clouds are few.
10. Use direct evaporative cooling in dry climates.
11. Use indirect evaporative cooling in slightly humid climates.
12. Use earth cooling mainly in the North and the West. Condensation can be a problem in humid areas.
13. Use solar chimneys to increase summer ventilation.

Reference

Schubert, R. P., and P. Hahn. In *Progress in Passive Solar Energy Systems*. Boulder, CO: American Solar Energy Society, 1983.

Resources

FURTHER READING

(See Bibliography in back of book for full citations.)

Abrams, D. W. *Low-Energy Cooling*.
Akbari, H., et al. *Cooling Our Communities: A Guidebook on Tree Planting and Light-Colored Surfacing*.
Allard, F., ed. *Natural Ventilation in Buildings*.
Baird, G. *The Architectural Expression of Environmental Control Systems*.
Boutet, T. S. *Controlling Air Movement: A Manual for Architects and Builders*.
Brown, G. Z., and M. DeKay. *Sun, Wind, and Light: Architectural Design Strategies*, 3rd ed.
Cook, J. "Cooling as the Absence of Heat."
———, ed. *Passive Cooling*.
Daniels, K. *The Technology of Ecological Building: Basic Principles and Measures, Examples and Ideas*.
Environmental Protection Agency. "Cooling Our Communities."
Givoni, B. *Climate Considerations in Building and Urban Design*.
———. *Man, Climate and Architecture*.
———. *Passive and Low Energy Cooling of Buildings*.
Golany, G. *Housing in Arid Lands—Design and Planning*.
Konya, A. *Design Primer for Hot Climates*.
Kwok, A., and W. Grondzik. *The Green Studio Handbook: Environmental Strategies for Schematic Design*, 2nd ed.
Olgyay, V. *Design with Climate*.
Santamouris, M., and D. Asimakopoulos, eds. *Passive Cooling of Buildings*.
Solar Energy Research Inst. *Cooling with Ventilation*.
Stein, B., J. S. Reynolds, W. T. Grondzik, and A. G. Kwok. *Mechanical and Electrical Equipment for Buildings*, 11th ed.
Underground Space Ctr., Univ. Minn. *Earth Sheltered Housing Design: Guidelines, Examples, and References*.
Watson, D., and K. Labs. *Climatic Design: Energy Efficient Building Principles and Practices*.

CHAPTER 11

SITE DESIGN, COMMUNITY PLANNING, AND LANDSCAPING

Study nature, love nature, stay close to nature. It will never fail you.
Frank Lloyd Wright

The sun is fundamental to all life. It is the source of our vision, our warmth, our energy, and the rhythm of our lives. Its movements inform our perceptions of time and space and our scale in the universe. . . . Assured access to the sun is thus important to the quality of our lives.
Ralph L. Knowles,
Sun Rhythm Form

11.1 INTRODUCTION

The heating, cooling, and lighting of a building are very much affected by the site and community in which the building is located. Although many aspects of a site have an impact on a building, only those that affect solar access and wind penetration will be discussed here. All of the strategies discussed fall under tiers one and two of the three-tier design approach (Fig. 11.1a).

The ancient Greeks realized the importance of site and community planning for the heating and cooling of buildings. Since they wanted their buildings to face the winter sun and reject the summer sun, their new towns were built on southern slopes and the streets ran east–west whenever possible. The ancient Greek city of Olynthus was planned so that most buildings could front on east–west streets (Fig. 11.1b). See Figure 2.16 to understand how the buildings were designed to take advantage of this street layout. The ancient Greeks considered their solar design of buildings and cities to be modern and civilized.

The Romans were also convinced of the value of solar heating, so much so that they protected solar access by law. The Justinian Code of the sixth century states that sunshine may not be blocked from reaching a heliocaminus (sunroom).

While winter heating was critical to the ancient Greeks and Romans, summer shade was also very desirable. By building continuous rows of homes along east–west streets, only the end units would be exposed to the low morning and afternoon summer sun.

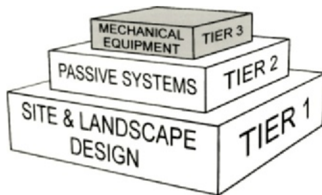


Figure 11.1a The heating, cooling, and lighting needs of a building as influenced by the site and community are best and most sustainably achieved by the three-tier design approach, and this chapter covers tiers one and two.

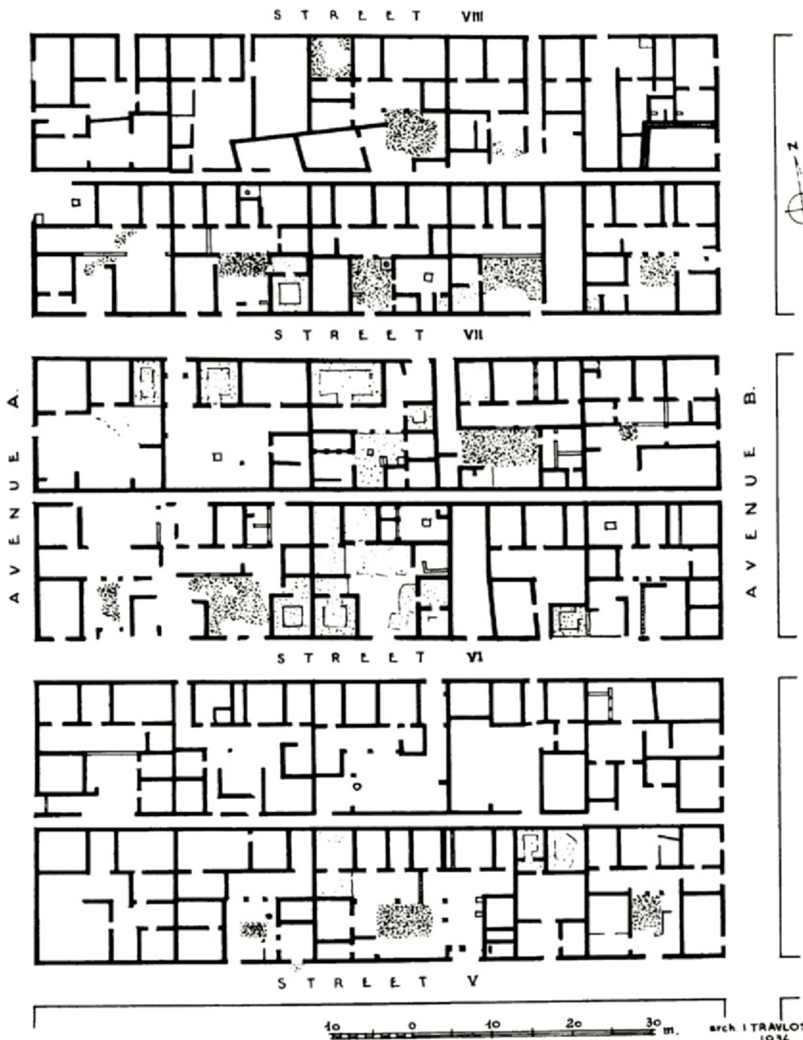


Figure 11.1b The ancient Greek city of Olynthus was oriented toward the sun. (From *Excavations at Olynthus*. Part 8, The Hellenic House © Johns Hopkins University Press, 1938.)

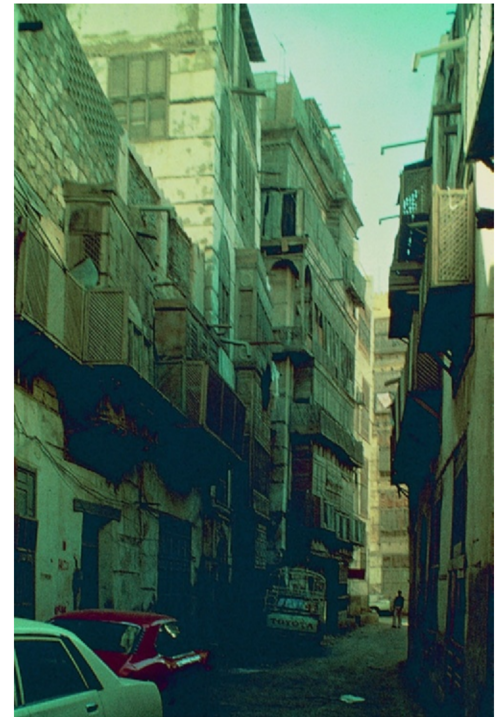


Figure 11.1c Multistory buildings facing narrow streets create desirable shade in very hot climates, as here in Jidda, Saudi Arabia. (Photograph by Richard Millman.)



Figure 11.1d The shading structure over this Moroccan street blocks much of the sun but still allows air and daylight to filter through. (Courtesy of the Moroccan National Tourist Office.)



Figure 11.1e This colonnade in Santa Fe, New Mexico, protects pedestrians from rain as well as sun, and it shades the windows and walls.

In climates with very hot summers and mild winters, shade is more desirable than solar access. Often multistory buildings are built on narrow streets to create shade both for the street and for the buildings (Fig. 11.1c). When buildings are not tall enough to cast much shade, pedestrian streets can have their own shading system (Fig. 11.1d). And when protection from rain as well as sun is desirable, arcades and colonnades are frequently used (Fig. 11.1e).

Wind is also an important factor in vernacular design. When there is too much wind and the temperature is cool, windbreaks are common, and windbreaks of dense vegetation are most common (Fig. 11.1f). On the other hand, when the climate is warm



Figure 11.1f Farms in the Shimane Prefecture of Japan use L-shaped windbreaks for protection from the cold wind. (From *Sun, Wind, and Light: Architectural Design Strategies*, by G. Z. Brown, © John Wiley, 1985.)



Figure 11.1g In hot and humid climates, such as that of Tocamacho, Honduras, buildings are set far apart to maximize the cooling breezes. (From *Sun, Wind, and Light: Architectural Design Strategies*, by G. Z. Brown, © John Wiley, 1985.)

and humid, cross-ventilation is very desirable. Many native communities maximize the benefit of natural ventilation by building far apart and by eliminating low vegetation that would block the cooling breezes (Fig. 11.1g).

11.2 SITE SELECTION

When the United States was first settled and land was still plentiful, farms were built almost exclusively on south slopes. It was well known that a south slope is warmer and has the longest growing season. When a choice of sites is available, a south slope is still the best for most building types.

In the winter, the south slope is warmest for two reasons. It receives the most solar energy on each square foot of land because it most directly faces the winter sun (Fig. 11.2a). This phenomenon, called the cosine law, was discussed in depth in Chapter 6. The south slope also experiences the least shading because objects cast their shortest shadows on south slopes (Fig. 11.2b).

Figure 11.2c illustrates the variation in microclimate with different slope orientations. The south slope gets the most sun and is the warmest in the winter, while the west slope is the hottest in the summer. The north slope is the shadiest and coldest, while the hilltop is the windiest location. Low areas tend to be cooler than slopes because cold air drains into them and collects there.

The best site for a building on hilly land depends on both climate and building type. For envelope-dominated buildings, such as residences and small office buildings, the climate would suggest the sites shown in Figure 11.2d.

For example, in

Cold climates: South slopes maximize solar collection and are shielded from cold northern winds. Avoid the windy hilltops and low-lying areas that collect pools of cold air.

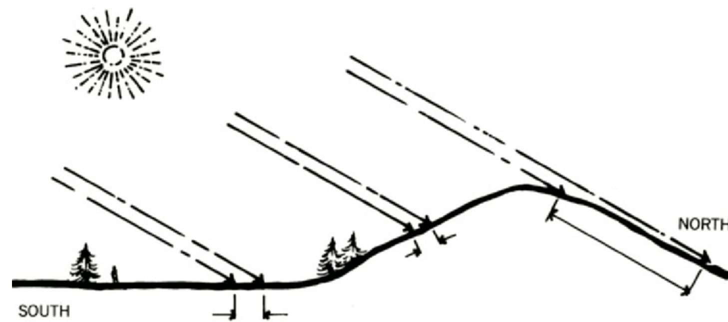


Figure 11.2a In winter, south-sloping land receives the most sunshine because of the cosine law. For the same reason, north-facing slopes receive very little solar heating because a given sunbeam is spread over much more land.

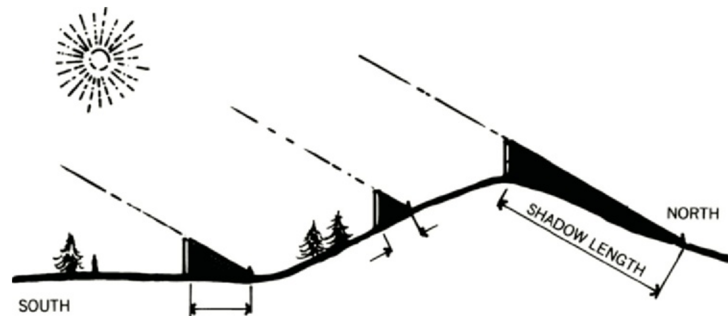


Figure 11.2b South-sloping land also experiences the least shade.

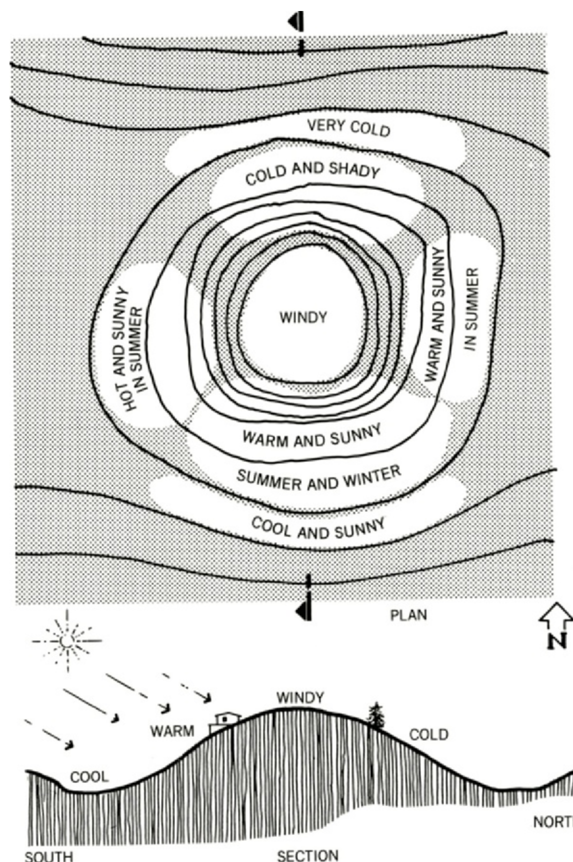


Figure 11.2c Microclimates around a hill.

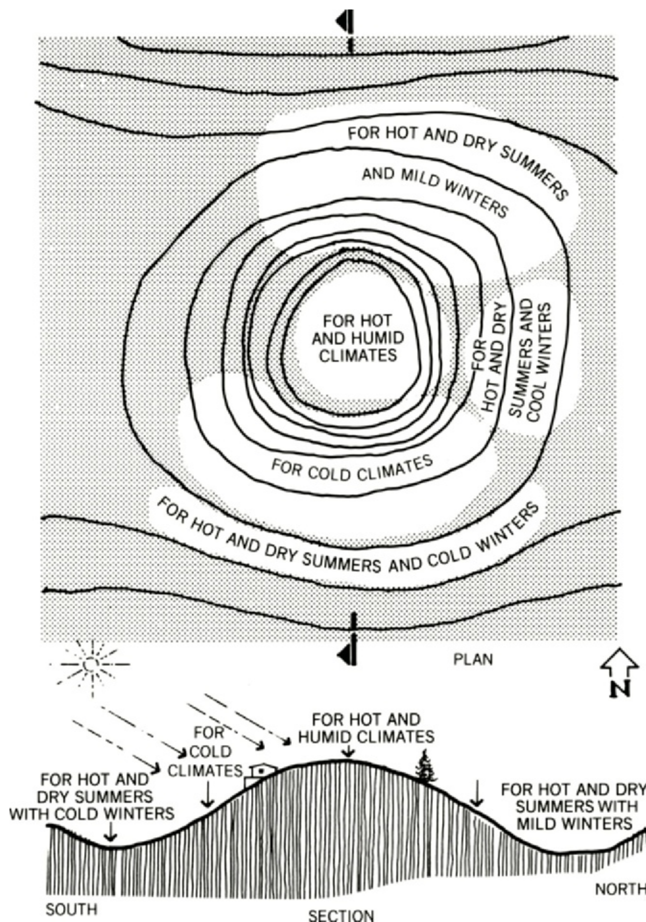


Figure 11.2d Preferred building sites around a hill in response to climate for envelope-dominated buildings.

Hot and dry climates: Build in low-lying areas that collect cool air. If winters are very cold, build on the bottom of the south slope. If winters are mild, build on the north or east slope, but in all cases avoid the west slope.

Hot and humid climates: Maximize natural ventilation by building on hilltops but avoid the west side of hilltops because of the hot afternoon sun.

For internally dominated buildings, such as large office buildings that require little if any solar heating, the north and northeast slopes are best. Also appropriate are the cool, low-lying areas, especially to the north of hills.

11.3 SOLAR ACCESS

Nothing is as certain and consistent as the sun's motion across the sky. It is, therefore, possible to design for solar access with great accuracy, barring the possibility that future construction on neighboring property will block the sun. If neighbors are sufficiently far away or if restrictions exist on what can be built next door, solar access can be assured.

Although laws protecting solar access are rare, they do exist in the United States and they have existed for centuries in England. These legal aspects of solar access will be considered later. A discussion of the physical principles of solar access must come first.

In Chapter 6, the sun's motion was explained by means of a sky dome. That part of the sky dome through which useful solar energy passes was called the **solar window** (Fig. 6.8b). The bottom of this solar window is defined by the sun path of the winter solstice (December 21). The sides of the window are usually set at 9 A.M. and 3 P.M. The window thus includes the time period during which more than 80 percent of the winter solar radiation is available. Of course, if sunlight is available before 9 A.M. or after 3 P.M., it should be used.

The conical surface generated by the sun's rays on the winter solstice from 9 A.M. to 3 P.M. is called the solar-access boundary. Any object that projects through this surface will obstruct the winter sun (Fig. 11.3a). A north–south section through this **solar-access boundary** is shown in Fig. 11.3b.

Some books suggest, however, that if the trees are deciduous they can project through the solar access boundary (Fig. 11.3c), because they

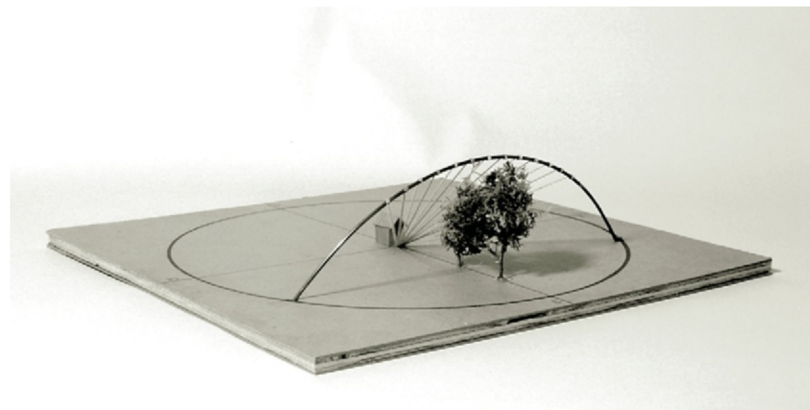


Figure 11.3a The solar-access boundary is a conical surface generated by sunrays on December 21 from 9 A.M. to 3 P.M. Any trees or buildings projecting through this surface will obstruct solar access to the site.

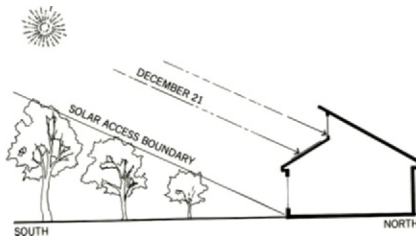


Figure 11.3b The solar-access boundary determines how high objects can be before they obstruct the sun.

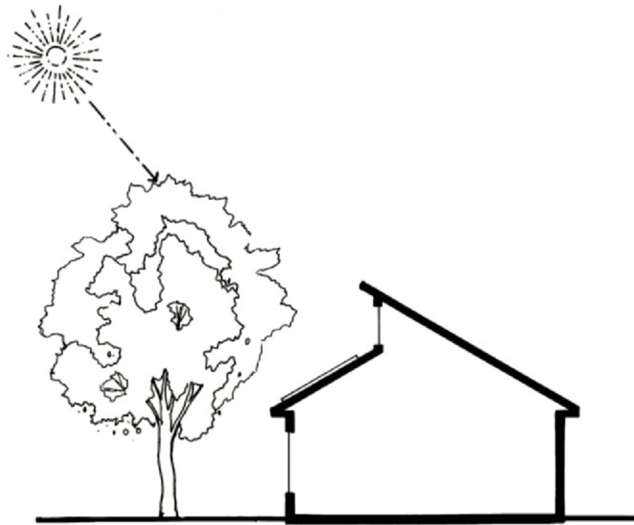


Figure 11.3c Trees on the south side of a building are problematic, because they can shade active solar, PV arrays, and block desirable daylight in the summer.

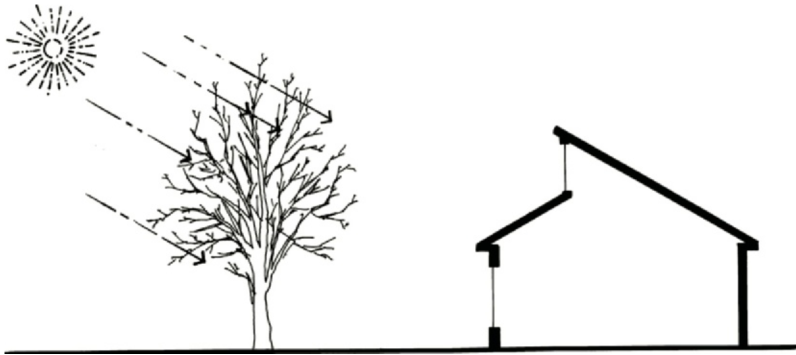


Figure 11.3d Even without leaves, deciduous trees still block 30 to 60 percent of sunshine.

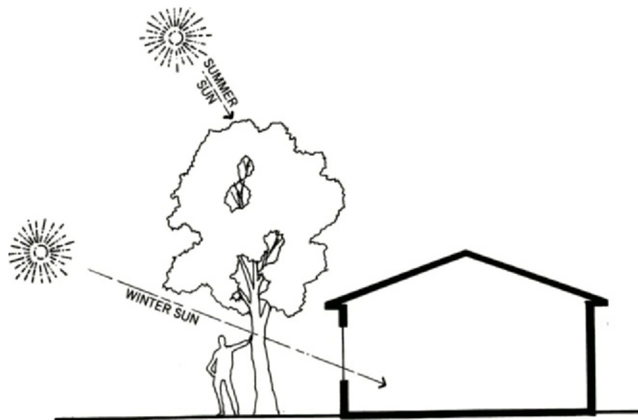


Figure 11.3e If large desirable trees exist on the south side in hot climates, trim the lower branches to form a high canopy.

will create valuable summer shade while allowing access to the winter sun. Unfortunately, deciduous trees without their leaves still block a significant amount of sunlight. Most deciduous trees block between 30 to 60 percent of the winter sun (Figs. 11.3d and 11.9c). Furthermore, if the roof has collectors for domestic hot water, pool heating, and/or PV, it should also not be shaded in the summer. Thus, on the south side of buildings, trees should usually be kept below the solar-access boundary (Fig. 11.3b).

If large trees already exist on the south side of a building in very hot climates with mild winters, it may not be appropriate to cut them down to improve the solar access. The summer shade from mature trees might be more valuable than the lost energy from the sun (Fig. 11.3e). However, in most climates, the energy from the sun is too valuable not to use. Every square foot (meter) of the south facade and south-facing roof should be used to collect daylight, PV electricity, and hot water all year long and passive solar in the winter.

11.4 SHADOW PATTERNS

When designing only one building on a site, solar access is best achieved by working with the solar-access boundary. When designing a complex of buildings or a whole development, **shadow patterns** are often useful for achieving solar access to all of the buildings. By drawing the shadow pattern for each building and tree, it is possible to quickly determine conflicts in solar access (Fig. 11.4a). The main difficulty with this technique is the generation of accurate shadow patterns.

A shadow pattern is a composite of all shadows cast during winter hours when access to the sun is most valuable. It is generally agreed that solar access should be maintained, if possible, from about 9 A.M. to 3 P.M. during the winter months. During those six hours, more

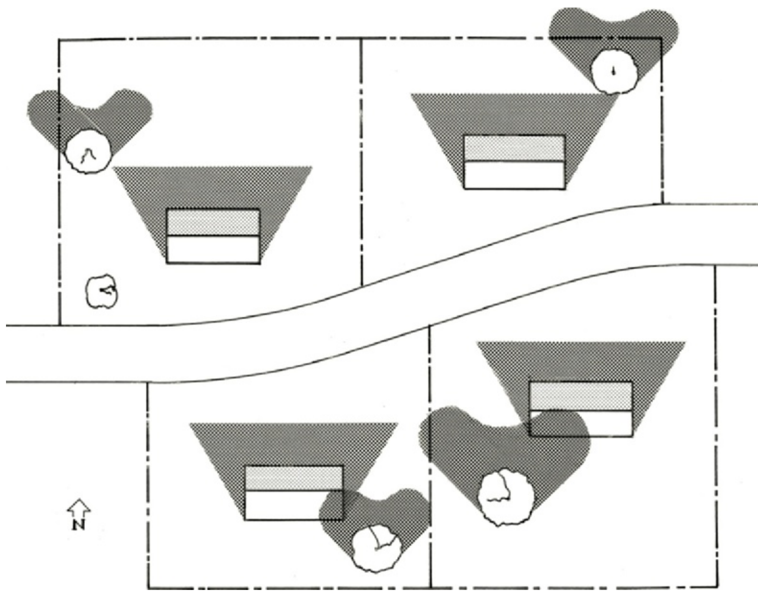


Figure 11.4a Shadow patterns demonstrate conflicts in solar access. Notice that the trees shade the lower two buildings during the winter.

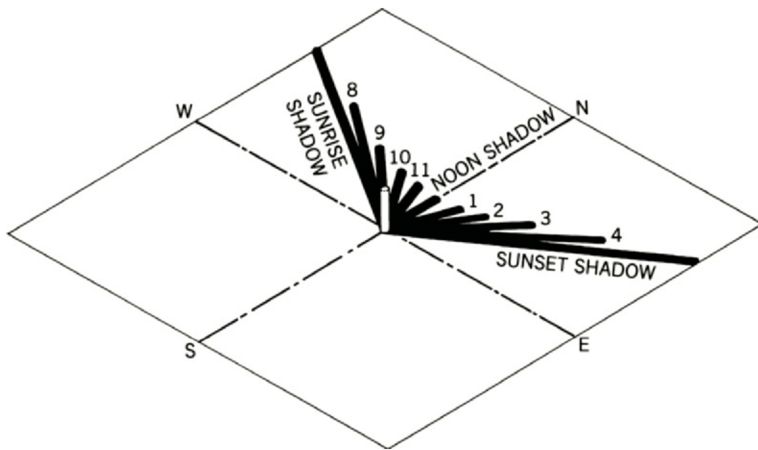


Figure 11.4b The shadows cast by a vertical pole from sunrise to sunset on December 21 vary with latitude.

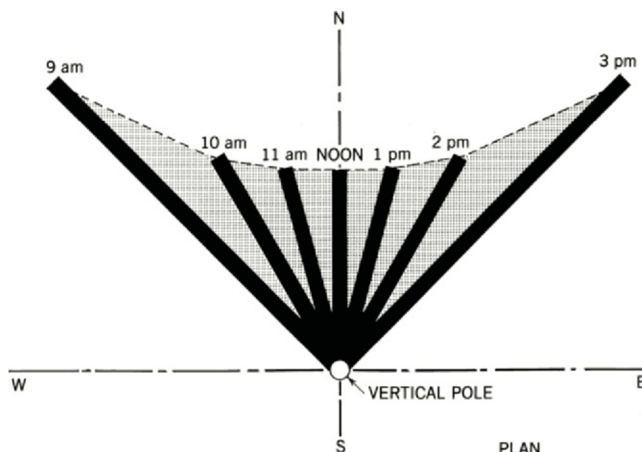


Figure 11.4c Plan view of the shadows cast by a pole at 36° N latitude on December 21 from 9 A.M. to 3 P.M.

than 80 percent of a winter's total daily solar radiation will fall on a building.

The easiest way to understand shadow patterns is by examining the shadows cast by a vertical pole. Figure 11.4b illustrates the shadows cast by a pole on December 21. The same pole is shown in plan in Fig. 11.4c with the shadows cast at each hour between 9 A.M. and 3 P.M. at 36° N latitude. The shaded area represents the land where solar access is blocked by the pole at some time during these hours and is called the shadow pattern of the pole. Of course, the taller the pole, the longer the shadow pattern. In addition, the shadow pattern will be longer at higher latitudes and shorter at lower latitudes.

To make the construction of shadow patterns easier, we can determine the shadow lengths only for the hours of 9 A.M., 12 noon, and 3 P.M., and then connect them with straight lines (Fig. 11.4d). The construction of a shadow pattern is further simplified by drawing the ends of the shadow pattern at 45°, which corresponds closely with 9 A.M. and 3 P.M. (actual azimuth at these times varies with latitude). The length of the shadow is determined by drawing a section through the pole at 12 noon

Table 11.4 Altitude Angles for Drawing Shadow Patterns for December 21

Latitude	Altitude at noon	Altitude at azimuth 45°
0	67	56
4	63	50
8	59	45
12	55	40
16	51	35
20	47	30
24	43	26
28	39	23
32	35	18
36	31	15
40	27	12
44	23	8
48	19	6
52	15	3
56	11	0

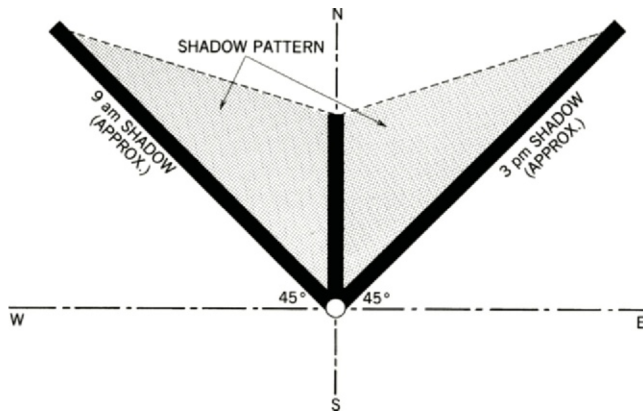


Figure 11.4d The simplified shadow pattern of a pole on December 21 is derived from the pole shadows of 9 A.M., 12 noon, and 3 P.M.

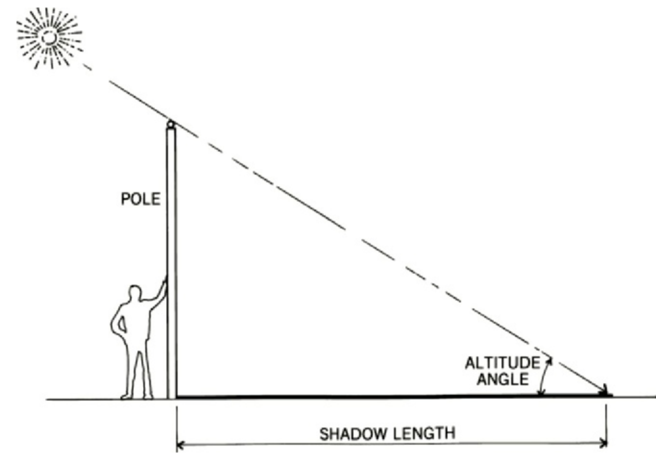


Figure 11.4e Shadow lengths are determined in section.

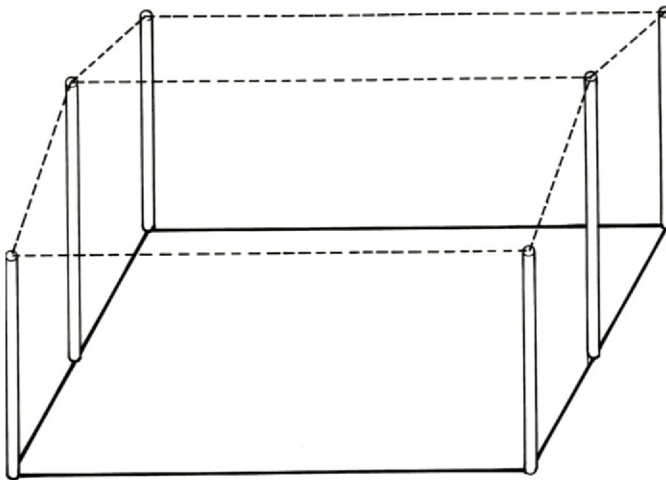


Figure 11.4f To generate the shadow pattern of a building, assume that the building consists of a series of poles.

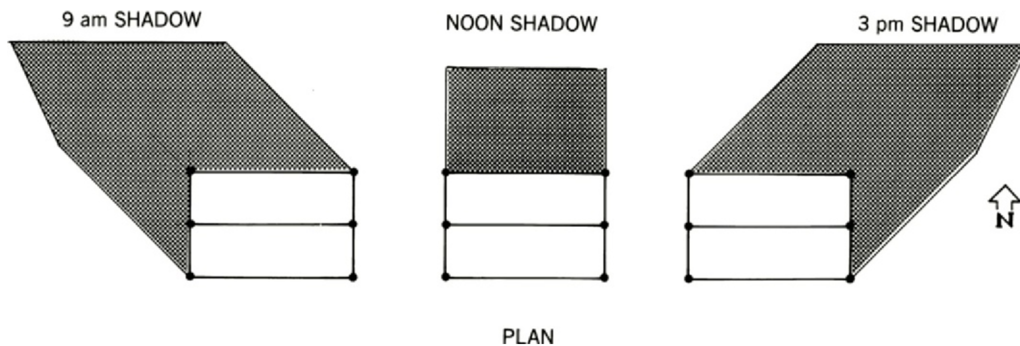


Figure 11.4g The morning, noon, and afternoon shadows on December 21 are constructed by assuming six poles. (After *Solar Energy Planning*, by P. Tabb, 1984.)

and 9 A.M./3 P.M. (45° azimuth) (Fig. 11.4e). Use Table 11.4 for the altitude angles of the sun at those times.

To construct the shadow pattern for a building, we assume that the building consists of a series of poles (Fig. 11.4f). The morning, noon, and afternoon shadows are then constructed from these poles (Fig. 11.4g). The composite of these shadows creates the shadow pattern (Fig. 11.4h). Additional poles would be required for more complex buildings.

The shading pattern, like the solar-access boundary, is affected by the slope of the land (Fig. 11.4i). Also, just because the footprint of a building is shaded, it cannot be assumed that the roof is also shaded. Because of the limitations and complexity of this graphic method, it is often easier to use physical models for generating accurate shadow patterns and for determining how a building is actually shaded. The use of physical models for this purpose will be explained below.

There is, however, a quick graphic method for creating approximate shadow patterns for simple buildings on flat land. Figure 11.4j illustrates this quick method for a gabled house, while Figure 11.4k illustrates the quick method for creating shadow patterns for trees.

It is important to remember that some solar access is better than none. Even if solar access cannot be provided from 9 A.M. to 3 P.M., assured access from 10 A.M. to 2 P.M. would still

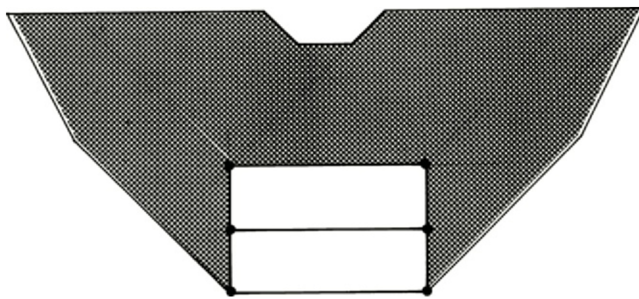


Figure 11.4h The shadow pattern is the composite of the morning, noon, and afternoon shadows. (After *Solar Energy Planning*, by P. Tabb, 1984.)

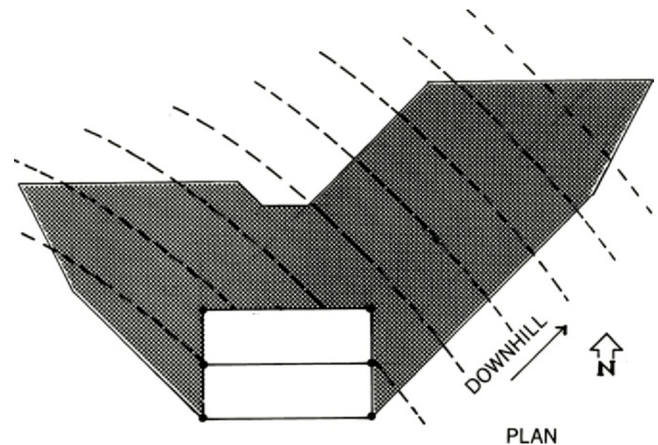
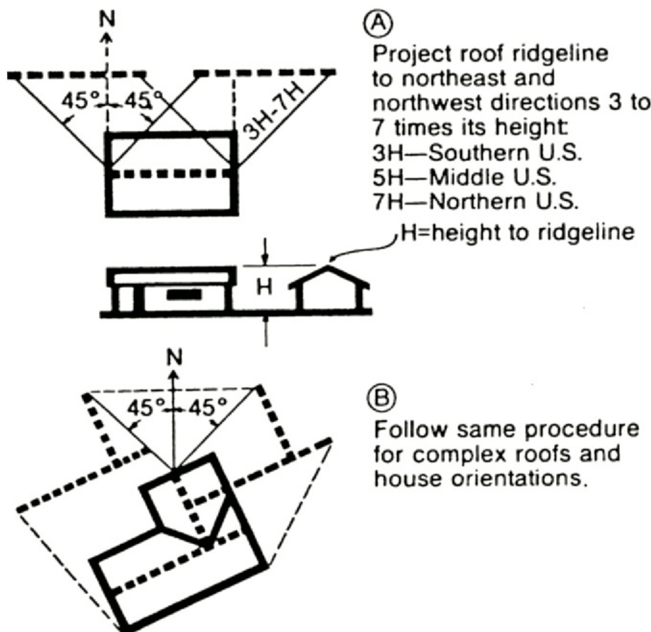


Figure 11.4i Sloping land changes the length and shapes of the shadow pattern. (After *Solar Energy Planning*, by P. Tabb, 1984.)



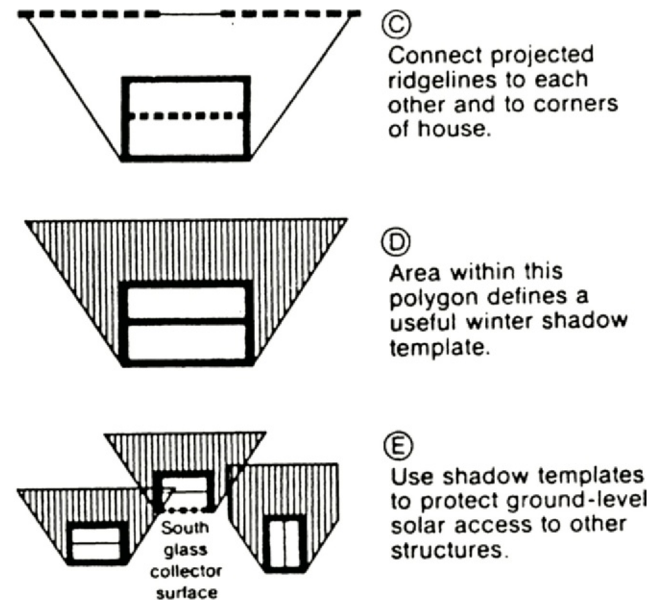


Figure 11.4j The quick method for constructing shadow patterns (templates) is shown. (Reprinted with permission from *Energy Conserving Site Design* by E. Gregory McPherson, © 1984, The American Society of Landscape Architects.)

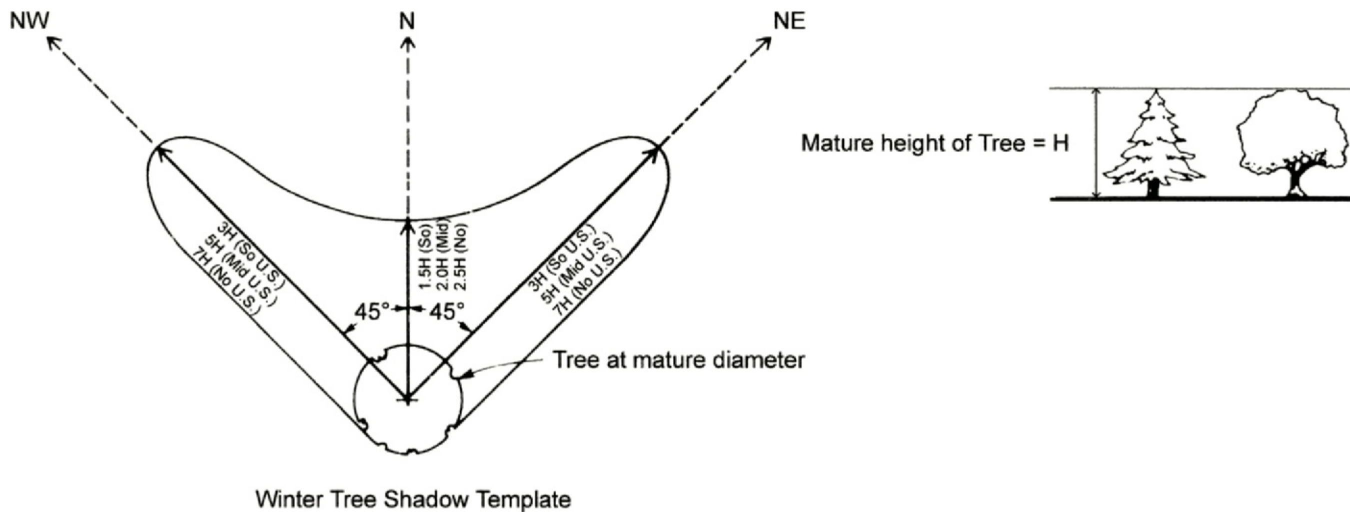


Figure 11.4k The quick method for creating shadow patterns (templates) for trees is shown. (Reprinted with permission from *Energy Conserving Site Design*, by E. Gregory McPherson, © 1984, The American Society of Landscape Architects.)

make available over 60 percent of the total daily solar radiation in the winter.

11.5 SITE PLANNING

As has been stated many times before, access to winter sun and avoidance of summer sun are greatly affected by building orientation. What street orientation will provide the most south and north windows and the fewest east and west windows for single-family housing, row housing, and urban buildings?

Fortunately, east-west streets provide the best orientation for the heating, cooling, and lighting needs of all building types. Not only are east and west windows minimized, but those there are shaded by neighboring buildings (Fig. 11.5a). On the other hand, with north–south streets there is little if any winter solar access, and the large east and west facades are exposed to the summer sun (Fig. 11.5b).

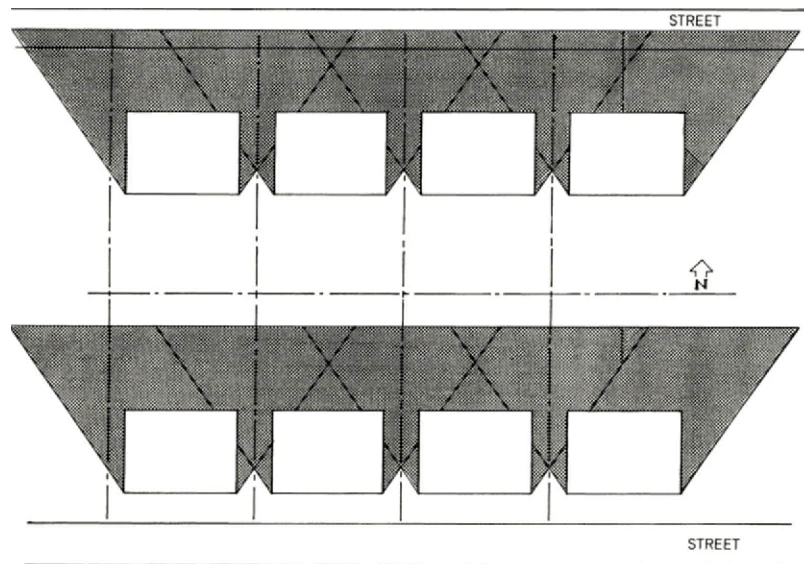


Figure 11.5a East–west streets are ideal for both winter solar access from the south and summer shading from the east and west.

It is usually possible to design new developments to maximize the number of lots fronting on east–west streets. A good example of this, the Village Homes subdivisions in Davis, California, is described at the end of the chapter (Figs. 11.13b and 11.13c).

The performance of free-standing buildings on north–south streets can be improved significantly by a number of different methods. Orienting the short facade to the street is the most obvious technique (Fig. 11.5c). The use of **flag lots**, interior lots with only driveway access to the street, is less common but is a very effective technique for achieving a good orientation for each building, as well as a quiet off-the-street location for some buildings (Fig. 11.5d). The increasing popularity of duplexes makes the technique shown in Figure 11.5e very promising.

Good orientation can also be achieved on diagonal streets if the buildings are rotated to face south. Although the practice of orienting facades parallel to streets is a widely held convention, it is almost never required by codes. There are a

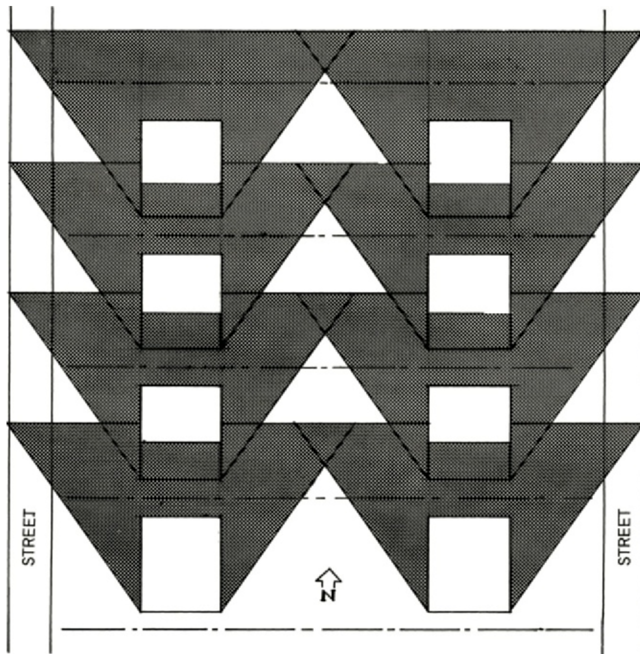


Figure 11.5b With conventional development, north–south streets promote neither solar access in winter nor shading on east or west facades in summer. Note how the buildings shade each other in the winter.

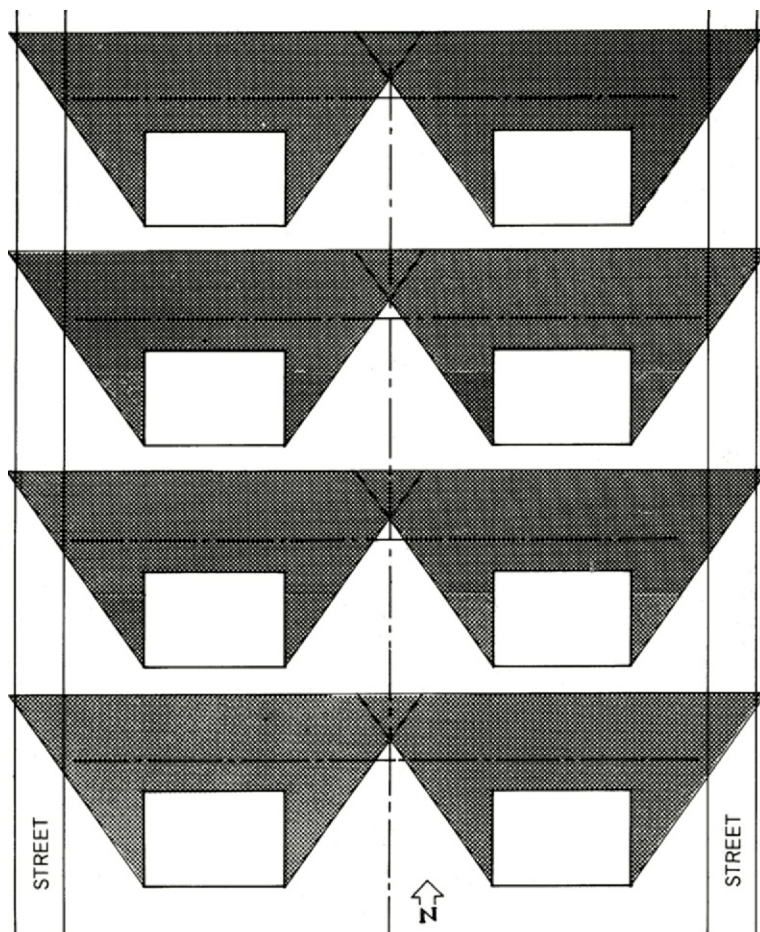


Figure 11.5c Buildings on north–south streets should have their narrow facade face the street.

number of benefits in the alternate arrangement shown in Figure 11.5f. Besides the better solar orientations, this arrangement yields much greater privacy since windows do not face each other. There are also aesthetic possibilities in this nonconventional design (Fig. 11.5g).

Although lots facing east–west streets have the greatest potential for good solar access and shading, these benefits are not guaranteed. For example, uneven setbacks can significantly reduce both winter sun and summer shading (Figs. 11.5h and 11.5i). Also, for buildings two or more stories high, the north–south separation between buildings becomes critical. Deep lots are better than shallow lots on east–west streets (Fig. 11.5j). However, when depth of lots is not sufficient, the designer must adjust setback requirements to benefit solar access.

Adjust the size, shape, and location of buildings to maximize solar access. Since streets are in most cases fairly wide, it is usually best to have the higher buildings and trees on the south side of east–west streets (Fig. 11.5k). If sufficient spacing is not possible, collect the sun at the roof level with south-facing clerestory windows and rooftop collectors (Fig. 11.5l).

The greatest challenge is to provide solar access to windows on the first floor for passive solar heating. Solar access for domestic hot water and PV is easier to achieve because much of the solar collection occurs during the higher sun angles of spring and summer and because the collectors are on the roof, which is shaded less than the south wall. Access for daylighting is also less demanding because of the year-round use of the sun and because both diffuse-sky radiation and reflected sunlight are useful. Thus, daylighting can be achieved with considerably less solar access than was described here for passive solar space heating. See Chapter 13 for guidelines on daylighting design.

East–west streets provide the best orientation for buildings!

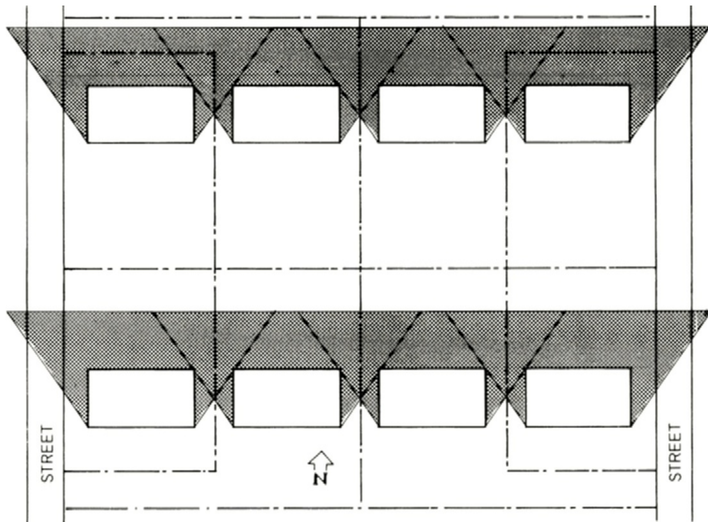


Figure 11.5d Flag lots (driveway looks like a flagpole) can achieve a good orientation for each building on a north–south street.

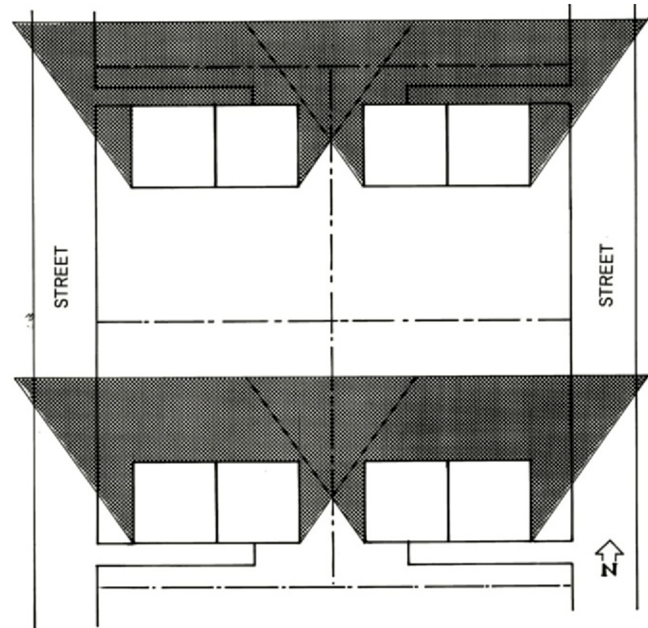


Figure 11.5e Duplexes can achieve good solar access even on a north–south street with this arrangement.

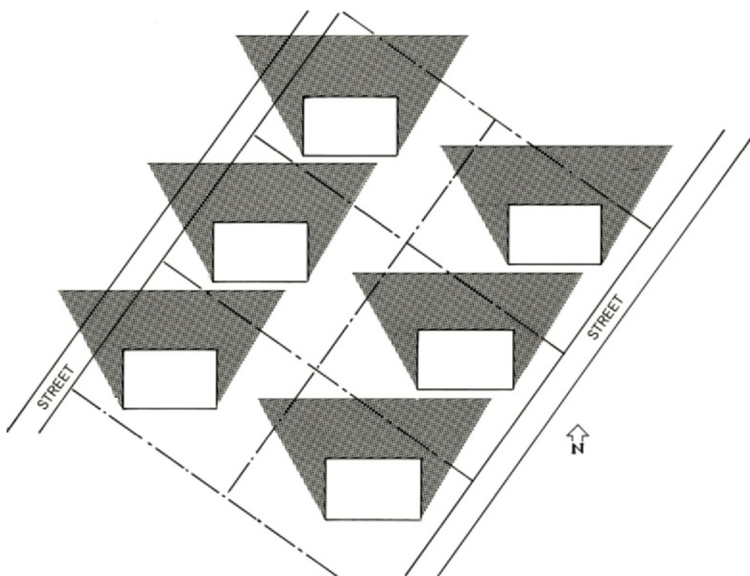


Figure 11.5f Even on diagonal streets, buildings can be oriented toward the south.



Figure 11.5g This site design shows a prototypical subdivision for solar access. It illustrates that although east–west streets are best, other street orientations and cul-de-sacs are still workable. (Courtesy of Prof. Michael Underhill, Arizona State University.)

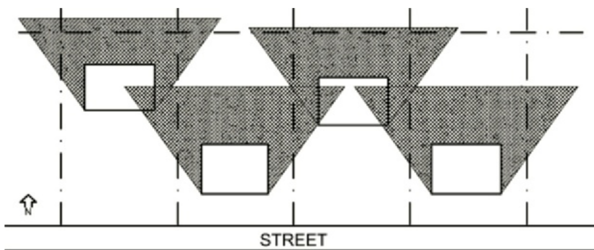


Figure 11.5h Uneven setbacks cause both winter and summer problems.

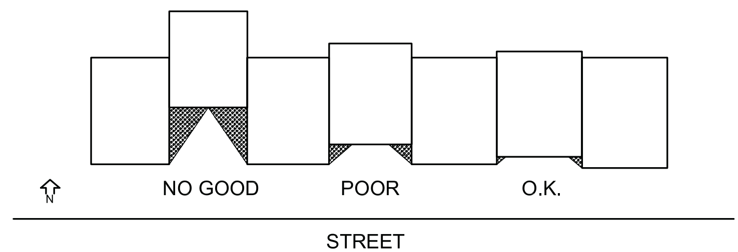


Figure 11.5i Very small setbacks, like those sometimes used in row housing, can be acceptable.

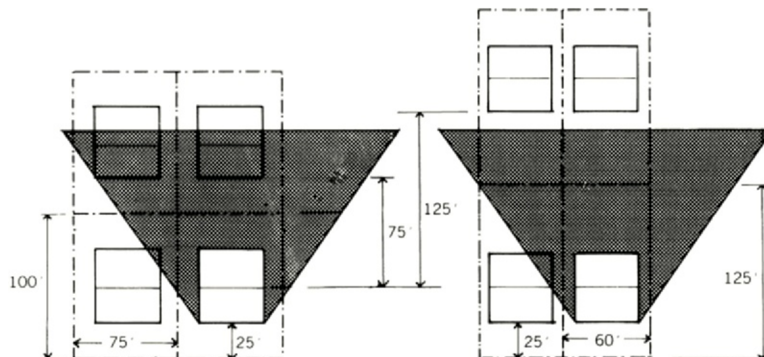


Figure 11.5j On east–west streets, deep lots are better than wide lots for solar access.

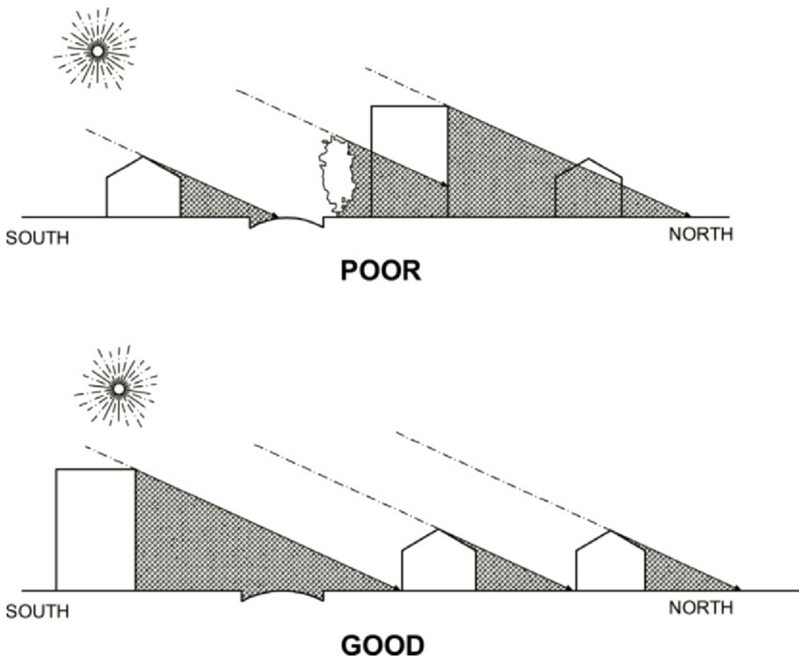


Figure 11.5k Place taller buildings and trees on the south side of east–west streets to take advantage of the wide right of way of the streets.

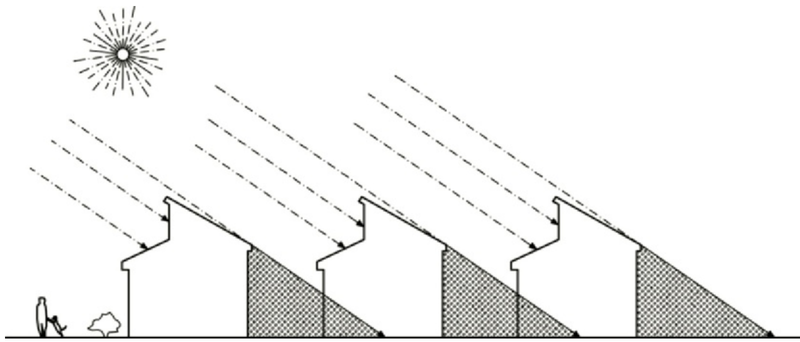


Figure 11.5l When solar access is not possible for the whole building, clerestories and active roof collectors should be used.

11.6 SOLAR ZONING

As the above discussion shows, solar access is very much dependent on what occurs on neighboring properties in all but the largest sites. Thus, solar-access laws are very important. However, since the United States does not have a doctrine of "ancient light" like that of England and since there is no constitutional right to solar access, state and local laws must be passed to ensure solar access. Although a few states, such as California and New Mexico, have passed solar-rights acts, most protection comes from zoning codes. Because of the many variables involved, this type of zoning must be very local in nature. Climate, latitude, terrain, population density, and local tradition all play an important part.

The amount of solar access to be achieved is another variable in the creation of zoning laws. If only the roofs of buildings require solar access, zoning will be least restrictive and easiest to achieve (Fig. 11.6a). Although south-wall access for passive solar is more difficult to achieve, it should be provided if possible. Providing south-lot access is less critical than it might seem because the sun is normally required there only in the spring and fall when the sun is higher in the sky. At least in northern climates, outdoor spaces are usually too cold for use in winter even if sunlight were available.

Solar zoning controls the shadows cast by a building on neighboring properties by defining the buildable volume on a site. Conventional zoning usually defines a rectangular solid (Fig. 11.6b), while solar zoning defines a sloped volume. Zoning can define this sloped buildable volume in several ways. In the **bulk-plane method**, a plane slopes up from the north property line (Fig. 11.6c). The author prefers this method because of its simplicity and because it provides more shading from the east and west summer sun. The **solar-envelope method** is more sophisticated but also more complicated

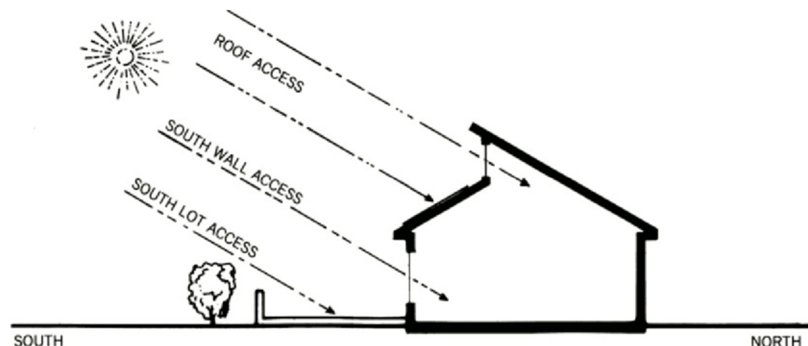


Figure 11.6a The three levels of solar access are shown.

(Fig. 11.6d). Professor Ralph Knowles at the University of Southern California has developed this method in great detail. It has the potential for not only ensuring high-quality solar access, but also generating attractive architecture (Figs. 11.6e and 11.6f). The **solar-fence method** is a third solar zoning strategy, and it utilizes an imaginary wall of prescribed height over which no shadow can be cast during certain hours (Fig. 11.6g).

In addition to zoning ordinances, several other possible ways exist to ensure solar access. Legal agreements or contracts can be set up between neighbors. For example, solar easements can be placed on neighboring properties.

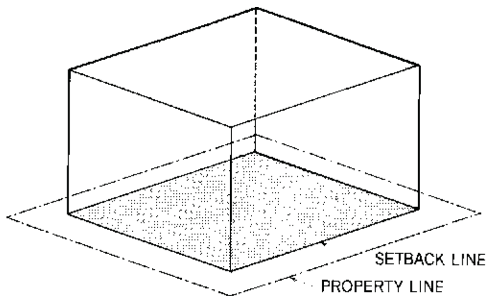


Figure 11.6b Conventional zoning usually defines a rectangular solid.



Figure 11.6e Example of architectural form encouraged by solar-envelope zoning. The model was created in Ralph Knowles's studio at the University of Southern California. (Photo of Ralph Knowles ©.)

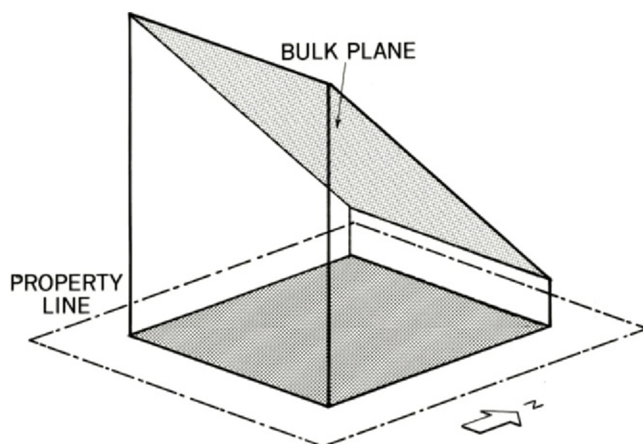


Figure 11.6c Bulk-plane zoning consists of an upper plane sloping down to the north.



Figure 11.6f This development in downtown Denver, Colorado, demonstrates the kind of architecture that solar-envelope zoning would encourage.

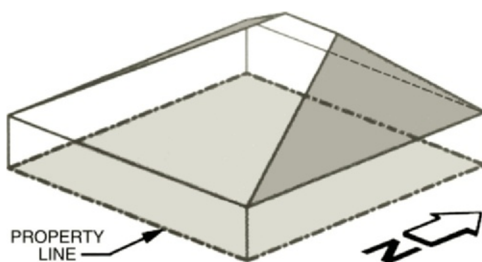


Figure 11.6d Solar-envelope zoning has upper sloping planes in the four compass directions.

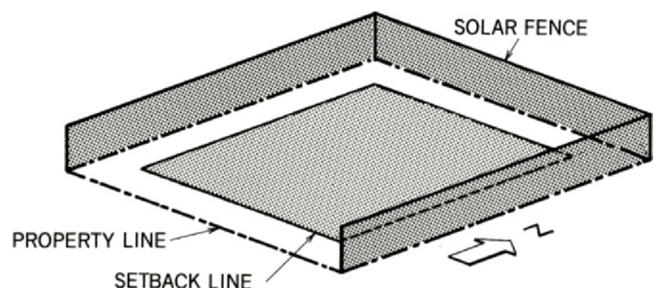


Figure 11.6g In solar-fence zoning, during certain hours shadows are limited to the height of the prescribed imaginary fence.

This is most effective in new developments where solar covenants and restrictions can guarantee solar access for all. For further discussion on the legal ways of ensuring solar access, see *Solar Energy Planning* by Phillip Tabb and *Protecting Solar Access for Residential Development*, U.S. Department of Housing and Urban Development.

11.7 PHYSICAL MODELS

As has been mentioned several times before, the use of a physical model in conjunction with a heliodon is a very powerful design tool. With a physical model of the site, solar access can be accurately determined no matter how complex the situation is. The shading due to any number of buildings, trees, and the lay of the land is, therefore, easy to analyze for any latitude, time of year, and time of day (Fig. 11.7a).

Physical models can also be used to easily generate shadow patterns no matter how complex the building or site. The following procedure is illustrated with a building on the side of a hill sloping down to the northeast at 32° N latitude.

Procedure for Creating Shadow Patterns

1. Place the model of the building with the site on the heliodon (see Appendix I for details on how to use the heliodon).
2. Illuminate the model to simulate shadows on December 21 at 9 A.M. (Fig. 11.7b).
3. Outline the shadow. (If drawing the shadow pattern directly on the model is not desirable, then first tape down a sheet of paper.)
4. Repeat steps 2 and 3 for 12 noon (Fig. 11.7c).

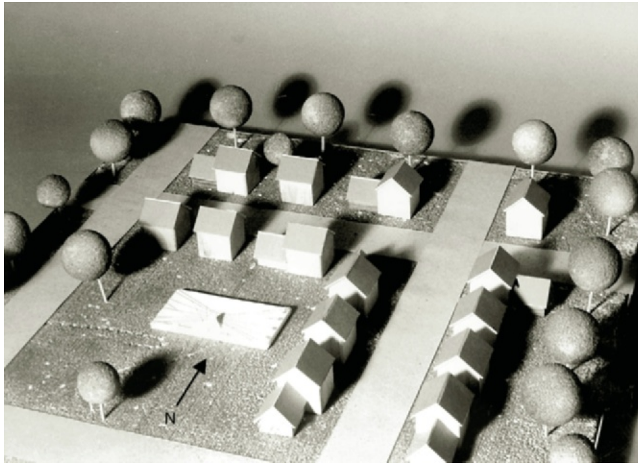


Figure 11.7a Physical modeling is an excellent design tool for providing each site with access to the sun. Note how an east–west street (left to right in the model) promotes solar access for buildings, while the north–south street inhibits it.

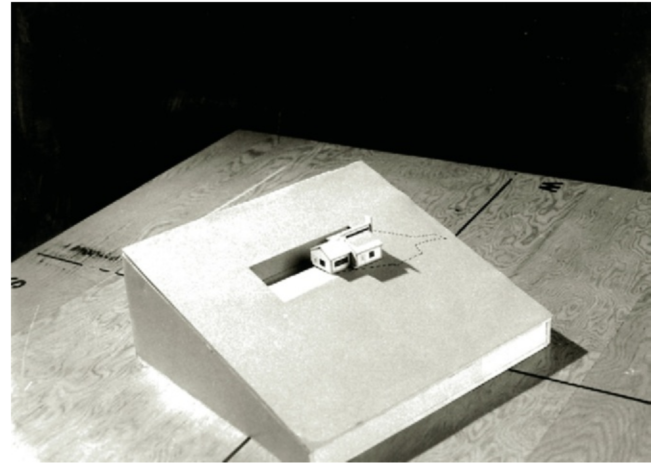


Figure 11.7c The shadow for December 21 at 12 noon is shown. Note the dashed outline for the 9 A.M. shadow.

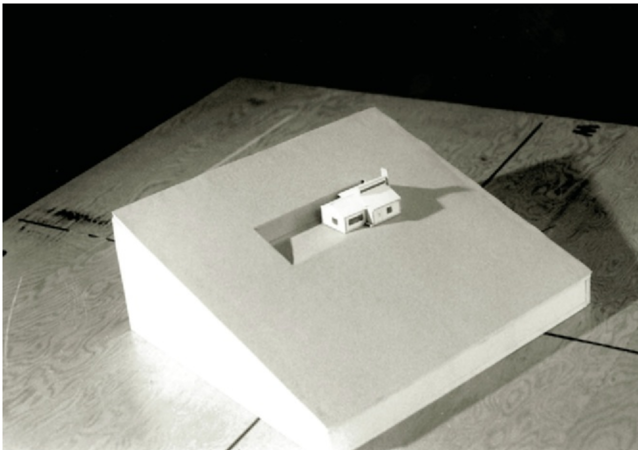


Figure 11.7b The shadow for December 21 at 9 A.M. is shown.

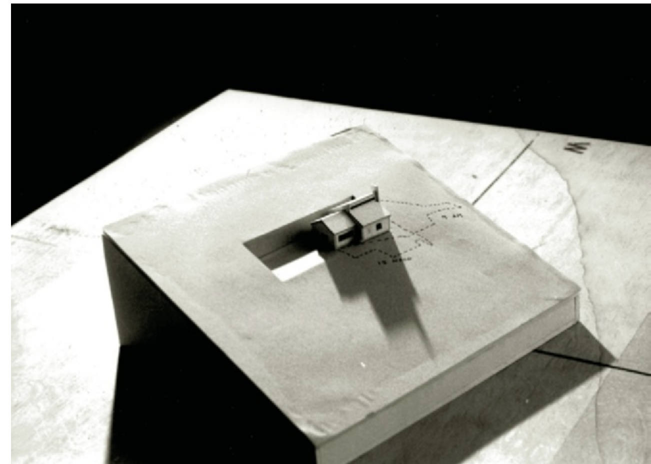


Figure 11.7d The shadow for December 21 at 3 P.M. is shown. Note the outlines for both the 9 A.M. and 12 noon shadows.

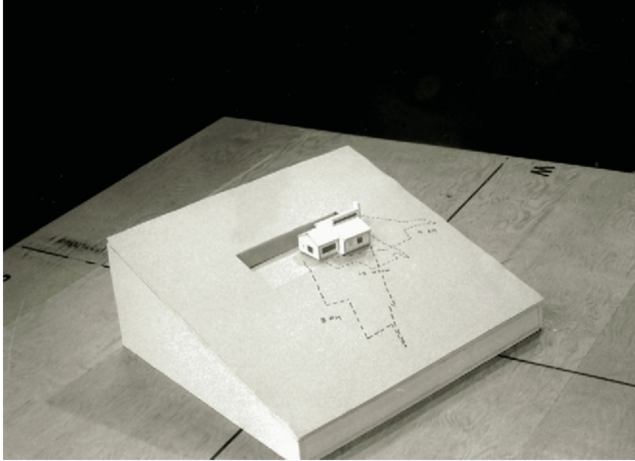


Figure 11.7e The composite of the three shadows forms the shadow pattern.

5. Repeat steps 2 and 3 again for 3 P.M. (Fig. 11.7d).
6. The composite of the above three shadows is a rough shadow pattern (Fig. 11.7e). A more refined shadow pattern can be obtained by also drawing the shadows for 10 A.M., 11 A.M., 1 P.M., and 2 P.M.

11.8 WIND AND SITE DESIGN

Since in most climates the wind is an asset in the summer and a liability in winter, a different wind strategy is required for summer and winter. Fortunately, this is made easier by a significant change in wind direction from summer to winter in many parts of the world (see the wind roses in Figs. 5.6d–5.6g).

Even if a particular region does not have a strong prevailing wind direction in winter, it is safe to say that the northerly winds will be the colder ones, and it is from these that the primary protection is required. Thus, it seems possible to design a site that diminishes the cooling effect of the northerly winds in the winter while still encouraging the more southerly summer winds.

The design implications of wind on the building itself are discussed in Chapter 10 (passive cooling) and Chapter 15 (infiltration). In this chapter, the impact of the wind on site design will be investigated.

In winter, the main purpose of blocking the wind is to reduce the heat loss that infiltration causes. Although infiltration is normally responsible for about one-third of the total heat loss in traditionally built homes, on a windy day on an open site, infiltration can account for more than 50 percent of the total heat loss in older buildings. Even with modern air barriers, infiltration is still a problem, especially at windows and doors. Since infiltration is approximately proportional to the square of the wind velocity, a small reduction in wind speed will have a large effect on heat loss. For example, if the wind speed is cut in half, the infiltration heat loss will be only one-fourth as large (Fig. 11.8a).

It is worthwhile to block the winter wind for several other reasons. Heat transmission through the building envelope is also affected by wind speed. The heat loss from door operations is greatly reduced if the entrance is protected from the wind. Finally, outdoor spaces are usable in winter only if they are protected from the cold winds.

Windscreens can effectively reduce the wind velocity by three methods: deflection of air to higher elevations, creation of turbulence, and absorption of energy by frictional drag. Solid windbreaks, such as buildings, tend to use the first two methods the most, while porous windbreaks, such as trees, rely mainly on the third method. Figure 11.8b illustrates the effect of porosity and height on the performance of a windbreak. Since the depth of wind protection is proportional to the height of the windbreak, the horizontal axis of the graph depicts multiples of the height of the windbreak. Notice that the densest windbreak results in the greatest reduction of air velocity but also has the smallest downwind coverage. Thus, dense windbreaks should

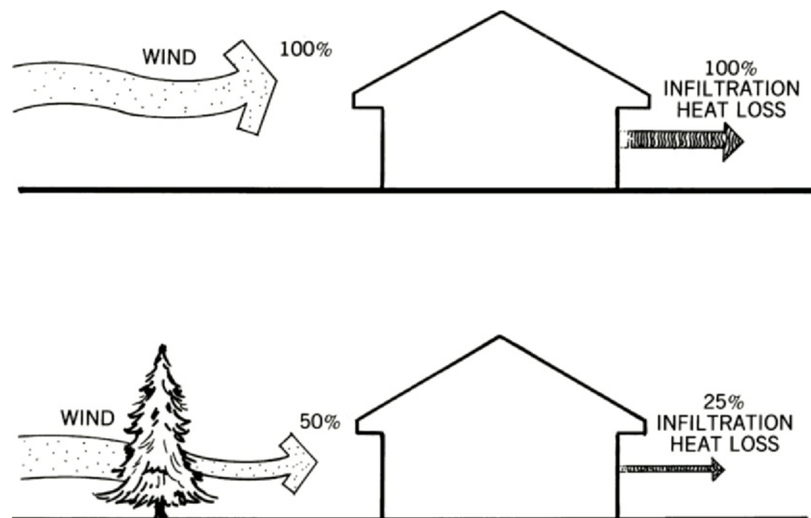


Figure 11.8a A small reduction in wind velocity results in a high reduction in heat loss.

be used on small lots or whenever the building is close to the windbreak, while medium-dense windbreaks would be better for protection at distances greater than four times the height of the windbreak.

Since windbreaks are never continuous, the end condition must be considered. At gaps or ends of windbreaks, the air velocity is actually greater than the free wind (Fig. 11.8c). This phenomenon can be an asset in the summer but certainly is not in the winter. The same undesirable situation arises in cities where buildings channel the wind along streets. A similar situation also occurs at passages through buildings, such as dogtrots (see Fig. 10.2q). Buildings raised on columns (e.g., Le Corbusier's pilotis) create very windy conditions at grade level and are recommended only for climates without cold winters (Fig. 11.8d). Even without underpasses, high-rise buildings often create such high winds at grade level that entrance doors are prevented from closing. This occurs because much of the wind hitting the facade of the building is deflected downward, as shown in Figure 11.8e. By the simple addition of a lower extension or large canopy, this downward wind can be deflected before reaching pedestrians at grade level (Fig. 11.8f).

To design a community or even a small development, it would be advantageous to place the higher buildings on the northern end. Not only will this arrangement block some of the cold northern wind, but it will also provide better access to the winter sun (Fig. 11.8g).

Windbreaks can also be used to control snow, dust, or sand, which are carried by the wind and will settle out in the "windstill" area behind a windbreak. Thus, snow fences are used in snow country, and garden walls surround buildings in areas prone to dust storms or sandstorms. For lightweight dust, the protective walls need to be as high as the building, but for relatively heavy sand even 6 ft (2 m) walls will reduce the wind velocity enough for the sand particles to settle out.

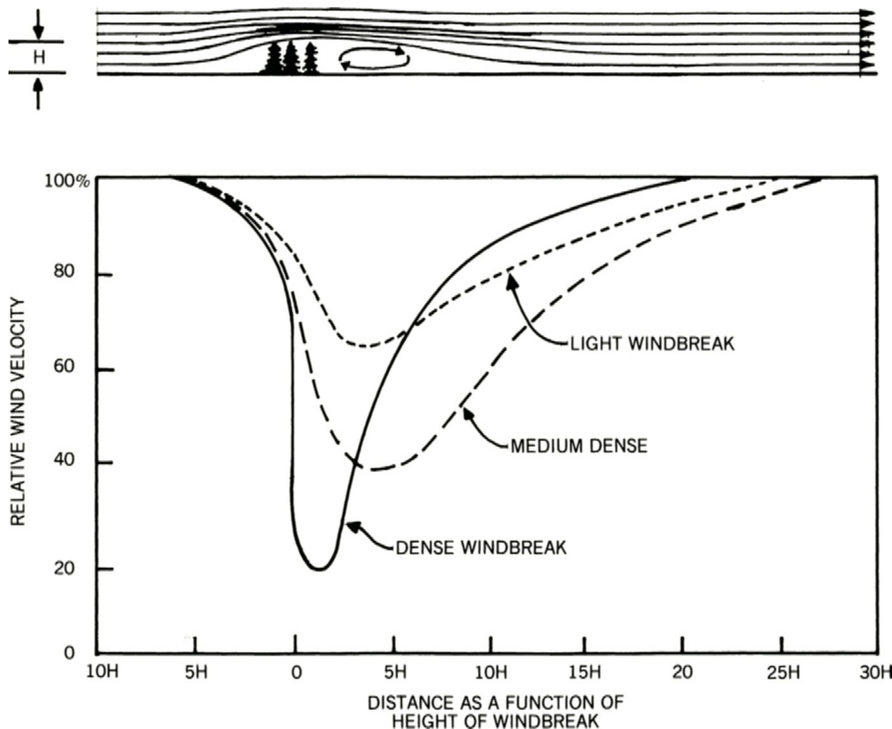


Figure 11.8b Wind protection is a function of both the height of a windbreak and its porosity. Note that the section is aligned with the graph. (After Naegeli (1946), cited in J. M. Caborn (1957). *Shelterbelts and Microclimate*, Edinburgh, Scotland: H. M. Stationery Office.)

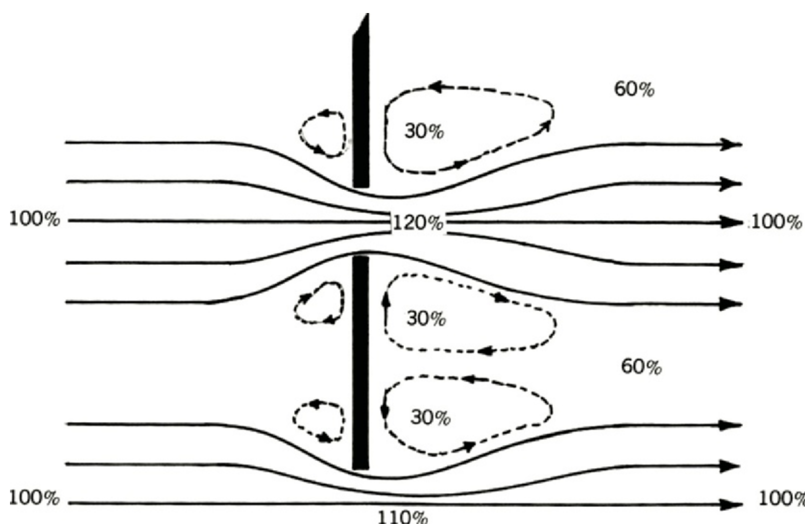


Figure 11.8c At gaps and at ends of windbreaks, the air velocity is actually greater than the free-wind speed.

Guidelines for Windbreak Design

1. The higher the windbreak, the longer the wind shadow (Fig. 11.8h).
2. To get full benefit of height, the width of the windbreak should be at least ten times the height (Fig. 11.8i).
3. The porosity of the windbreak determines both the length of the wind shadow and the reduction of wind velocity (Fig. 11.8b).

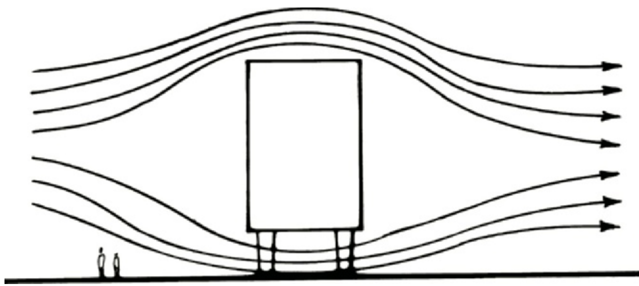


Figure 11.8d Buildings on columns (pilotis) experience very high wind speeds at ground level.

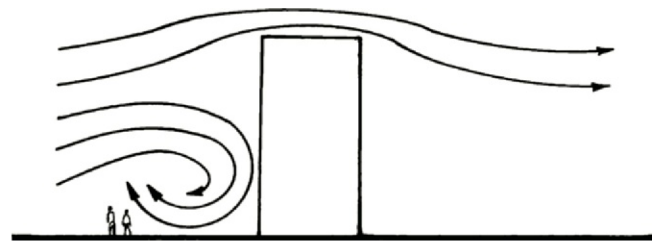


Figure 11.8e Tall buildings often generate severely windy conditions at ground level.

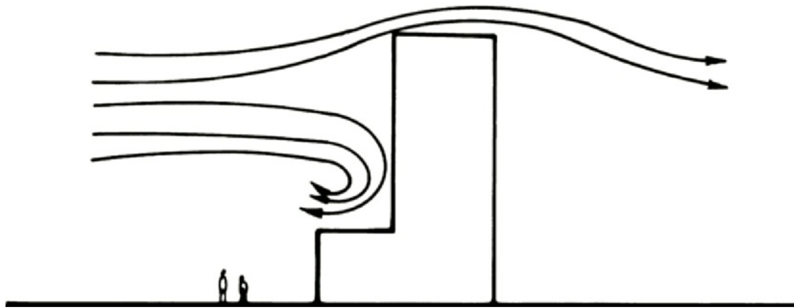


Figure 11.8f A building extension deflects winds away from ground-level areas.

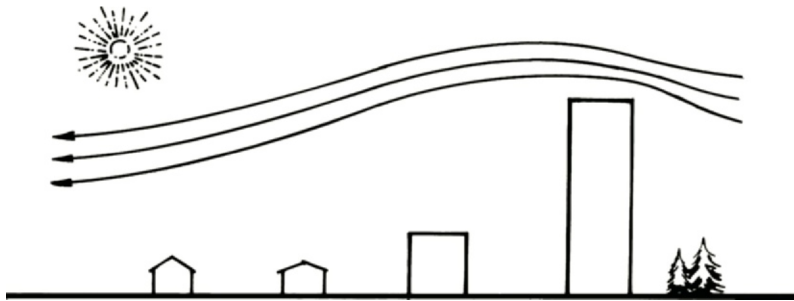


Figure 11.8g Tall buildings placed toward the north of a community not only protect it from the cold winter winds but also permit good solar access.

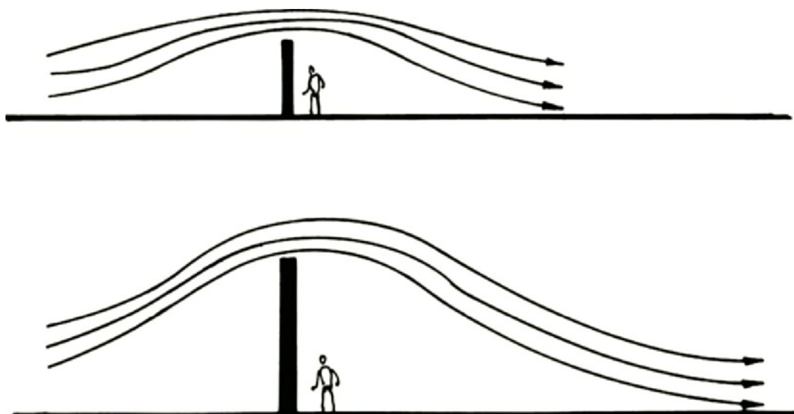


Figure 11.8h The higher the windbreak, the larger the wind shadow.

In summer or in climates with mild winters, breezes are welcome. Instead of being used for windbreaks, trees can be used to funnel more of the wind into the building (Fig. 11.8j). Even if the trees do not create a funnel, they can still increase ventilation by preventing the wind from easily spilling around the sides of the building (Fig. 11.8k). When there is no dominant summer wind direction, shade trees with a high canopy are desirable (Fig. 11.8l). If bushes are used, they should be placed away from the building, as shown in Figure 11.8m. If, instead, they are placed between the trees and buildings, the wind will be deflected over the building (Fig. 11.8n). This is the appropriate way to place bushes on the north side for winter wind protection.

By staggering the location of buildings, cooling breezes can be maximized (Fig. 11.8o). Since buildings cannot be moved for the winter, this strategy is appropriate only for hot and humid climates with mild winters. In cold climates where the priority is protection from the cold winter winds, row or cluster housing is most appropriate (Fig. 11.8p).

By placing a pool of water upwind or by building downwind from an existing lake, the air can be cooled by evaporation before entering a building. This strategy works best in hot and dry climates but can also be used in moderately humid areas. However, it is definitely counterproductive in very humid areas, where additional humidity is to be avoided. Pools and fountains were popular among the Romans in part for their cooling

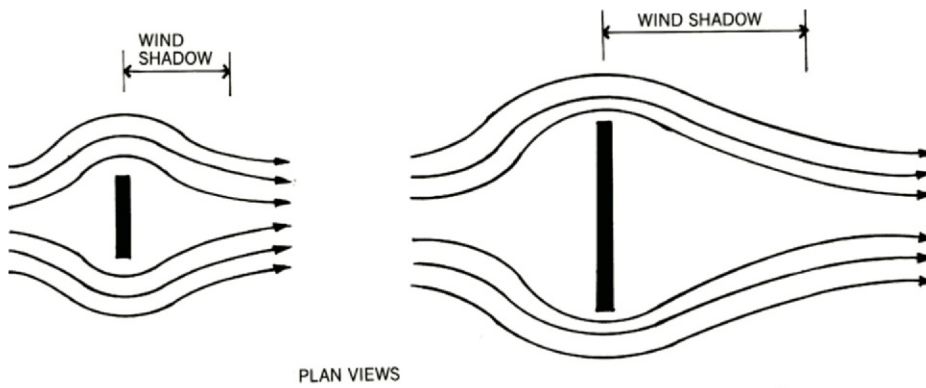


Figure 11.8i Up to a point, the width of a windbreak also affects the length of a wind shadow. In this plan view, both windbreaks are of the same height.

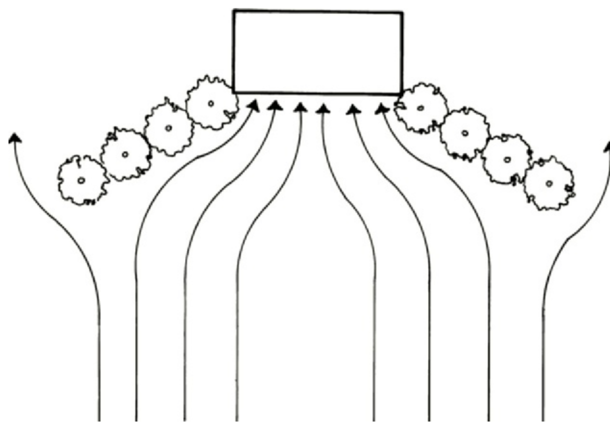


Figure 11.8j Trees and bushes can funnel breezes through buildings.

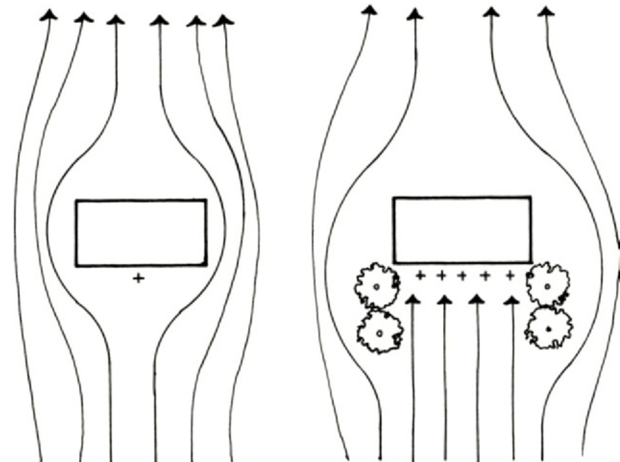


Figure 11.8k By preventing the wind from spilling around the sides of a building, a few trees or bushes can significantly increase natural ventilation.

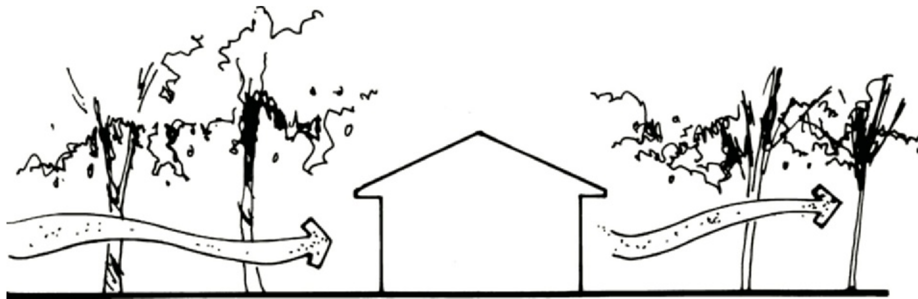


Figure 11.8l To maximize summer winds, use trees with high canopies.

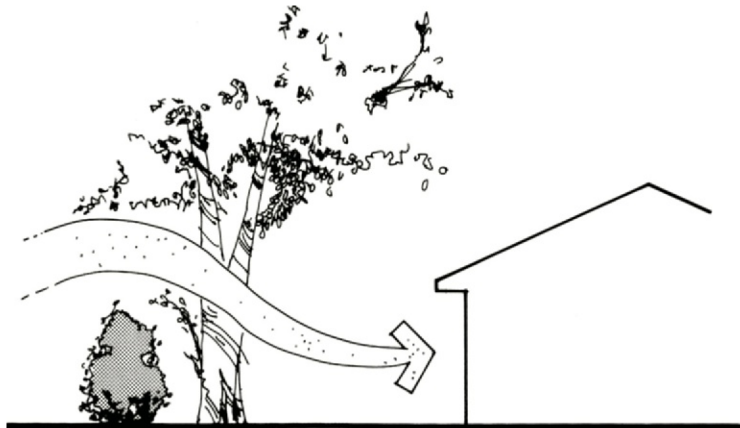


Figure 11.8m To maximize summer ventilation, place bushes away from the building, as shown.

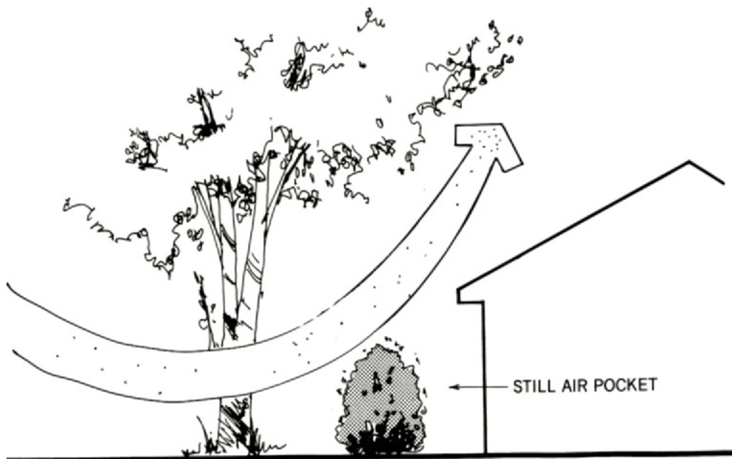


Figure 11.8n Placing bushes between the building and trees is good for winter wind protection but not good for summer ventilation.

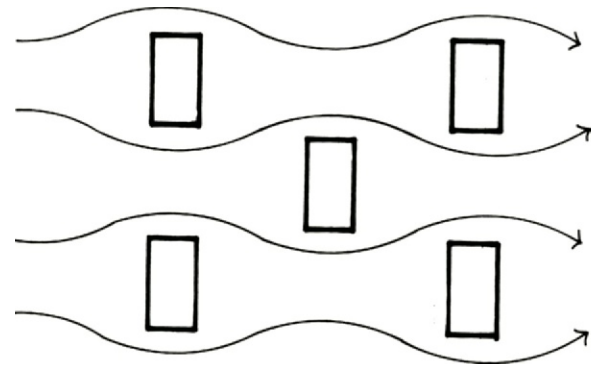


Figure 11.8o In hot and humid climates, buildings should be staggered to promote natural ventilation.

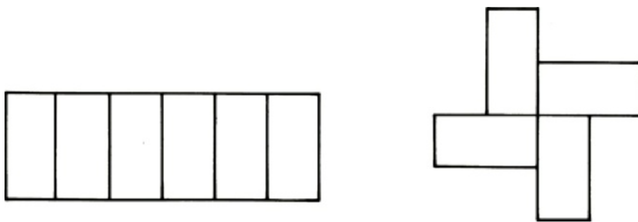


Figure 11.8p Use row or cluster housing for protection against wind in cold climates.



Figure 11.8q Large pools of water frequently helped cool Roman villas. The Getty Museum in California is a careful replica of a Roman villa. (Courtesy of the John Paul Getty Museum, Malibu, California. Julius Schulman, photographer.)



Figure 11.8r This dining terrace in the House of Loreio Tiburtino in Pompeii, Italy, was cooled by an indoor canal. A grapevine-covered pergola provided shade. The terrace is oriented to the south for winter heating. (Courtesy of Richard Kenworthy, photographer.)



Figure 11.8s In Taliesin West, near Phoenix, Arizona, Frank Lloyd Wright used pools and fountains to help cool the desert air.

benefits (Figs. 11.8q and 11.8r). Frank Lloyd Wright also recognized the advantages of pools and fountains in hot and dry climates. At Taliesin West, he used several pools and fountains, at least in part to cool the desert air (Fig. 11.8s).

11.9 PLANTS AND VEGETATION

Plants are immensely useful in the heating, cooling, and lighting of buildings. Through the proper location and selection of plants, well-designed landscaping can reduce the heating and cooling costs of a building as much as 25 percent. Although plants are very popular, they are usually used for their aesthetic and psychological benefits. The biologist E. O. Wilson holds the theory that people experience **biophilia**, an innate need for contact with a wide variety of species of animals and plants (Kellert and Wilson, 1993).

Plants have been shown to enhance human health and performance. People recovering in hospitals healed faster when they had views of greenery rather than views of another building (Ulrich, 1984). Larger views, especially of greenery, improved the scores of students in classrooms and the performance of office workers (Heschong, 2003). There is much evidence that people want and need views of green plants. Ideally, along with their aesthetic and psychological function, plants can act as windbreaks in the winter, as shading devices and evaporative coolers in the summer, and as light filters all year long (Figs. 11.9a and 11.9b). Vegetation can reduce erosion and attract wildlife. It can also reduce noise, dust, and other air pollution. It can reduce the level of carbon dioxide and increase the level of oxygen in the local air. It is sometimes most useful in blocking visual pollution or in creating privacy. For all of these reasons, planting and maintaining vegetation is a major sustainability strategy. Of course, just as in the design elements of the building itself, the more functions vegetation has, the better.

Before we discuss specific design techniques, some general comments about plants are in order. Perennial plants are usually better than annuals because they do not have to start from the beginning each year. Deciduous plants can be very useful for solar access, but some cautions are in order. It must be understood that even without leaves, the branches create significant shade (30 to 60 percent). A few trees shade even more of the winter sun. For example, some oaks hold onto their dead leaves and, thus, shade up to 80 percent of the winter sun (Fig. 11.9c). For colder climates, the best trees are those that have a dense summer canopy and are almost branchless in winter. Certain species will be deciduous only if the temperature gets cold enough. Thus, the same plant might be deciduous in the north and evergreen in the south. The times of defoliation in fall and foliation in spring vary with species. Some deciduous plants respond to length of daylight rather than temperature and, thus,

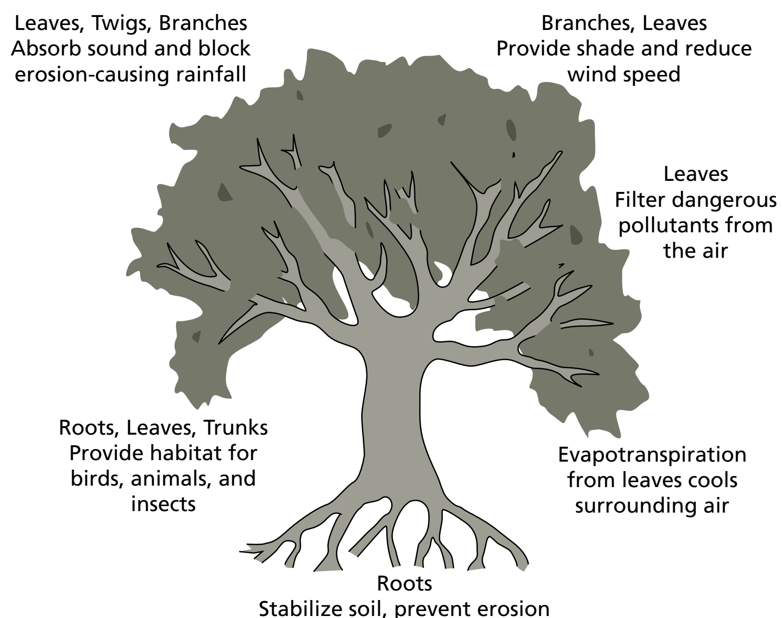


Figure 11.9a Besides the many benefits of trees described in this diagram, there are also psychological and aesthetic benefits.

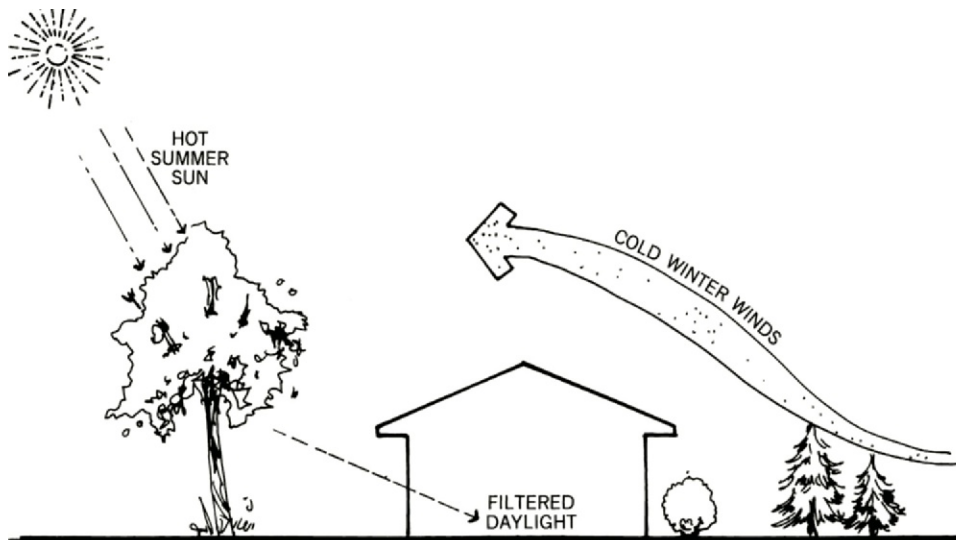


Figure 11.9b Plants can reduce winter heating and summer cooling as much as 25 percent. Plants can also improve the quality of daylight by filtering and diffusing the light.



Figure 11.9c Deciduous trees vary greatly in the amount of sunlight they block in the winter (30 to 60 percent). A few deciduous trees, like this particular oak, do not even lose their dead leaves until spring.

might defoliate at the wrong time. This is especially true when bright outdoor lighting at night confuses the biological timing of the plants.

Do not plant deciduous trees on the south side of a building!

The size and shape of a fully grown tree or shrub vary not only with species, but also with local growing conditions. See Table 11.9 for a sample of tree sizes, growth rates, percentage of winter and summer sun blockage, and time of fall defoliation and spring foliation. The location of the hardiness zones listed in the table are shown on the map of Figure 11.9d. Since a design is often based on the more mature size of a tree or bush, the growth rate is very important. Choosing a fast-growing tree or bush (2 ft [0.6 m] or more per year) is not always a good choice because most fast-growing trees are weak-wooded (have poor strength). However, a vine can be the ideal fast-growing plant. Since some vines grow as much as 40 ft (12 m) per year, a vine can create as much shade in three years as it can take a tree ten years to achieve. Physical strength is not required since a vine can be supported by a man-made structure such as a wall, a trellis, or a cable network. Unlike a tree, the growth of a vine can be directed exactly where it is needed in a fairly short time.

The growth rate of any tree, shrub, or vine can be accelerated by supplying ample nutrients and a steady source of water. A drip-irrigation system is excellent for this purpose. And, of course, starting with a large plant will further shorten the time required to reach maturity. Because urban trees often die or grow poorly due to a lack of good soil and water, they should be planted in the manner shown in Figure 11.9e.

Sometimes it is desirable to stop the growth of a plant when it has reached the desired size. That this is possible is proven by the existence of bonsai plants. The usual methods for creating bonsai include limiting the supply of nutrients, limiting the space for root growth, pruning, and using wire chokes to constrict the flow of nutrients. However, for the health of the plant, sufficient water must always be supplied.

Plants promote heating primarily by reducing infiltration and partly by creating still-air spaces next to buildings, which act as extra insulation. Use dense evergreen trees and shrubs for breaking the winter wind.

Summer cooling is more complicated, with most of the benefit

Table 11.2 Useful Trees

Name	Shap	Mature Size FT (M) HT × Spread	Growth Rate	Shade Provided Winter	Shade Provided Summer	Time in Leaf Fall Defoliates	Time in Leaf Spring in Leaf	USDA Hardiness Zone	Site Features
Acacia greggii (catclaw acacia)	spreading	15(5) × 10(3)	moderate	light	light	late	early	7–11	sun/dry soils
Acer platanoides (Norway maple)	round	50 (15) × 40(12)	moderate	light	dense	late	early	3–8	sun/well-drained soils
Acer rubrum (red maple)	oval/round	60(18) × 40(12)	fast	light	moderate	average	average	3–9	sun-partial shade/moist soils
Acer saccharinum (silver maple)	oval/round	75(23) × 40(12)	fast	moderate	dense	average	average	3–9	sun/wide variety of soils
Acer saccharum (sugar maple)	oval/ spreading	75(23) × 40(12)	moderate/fast	moderate	dense	average	average	3–8	sun/moist well-drained, acid soils
Betula nigra (river birch)	oval	30(9) × 20(6)	fast	light	moderate	early	early	4–9	sun/moist, sandy, acid soil
Cercidium fioridum (blue paloverde)	spreading	30(9) × 30(9)	moderate	light	light	late	late	8–11	sun/dry soils
Cercis canadensis (eastern redbud)	spreading	30(9) × 35(11)	moderate	light	light	late	average	4–9	sun-shade/moist-dry soils
Chilopsis linearis (desert willow)	vase	20(6) × 15(5)	fast	light	light	average	average	8–10	sun/dry, alkaline soils
Cornus fiorida (fiowering dogwood) select disease-resistant hybrids	round	35(11) × 35(11)	slow	light	medium	early	late	6–9	partial shade/moist, well-drained soils
Cornus kousa (Kousa dogwood)	round	25(8) × 20(6)	moderate	moderate	moderate	early	late	4–8	sun-part shade
Fagus sylvatica (European beech)	oval/round	100(30) × 70(21)	slow	moderate	dense	late	late	4–8	sun/moist, well-drained soils
Fraxinus pennsylvanica (green ash)	oval/round	50(15) × 30(9)	moderate	light	moderate	average	average	3–9	sun/wide variety of soils
Fraxinun veluntina (Arizona ash)	pyramid	35(11) × 25(8)	fast	light	moderate	average	average	7–9	sun/tolerates dry alkaline soil
Ginkgo biloba (ginkgo)	pyramid	70(21) × 40(12)	moderate/slow	light	dense	average	late	4–9	sun/wide variety of soils
Gleditsia triacanthos var. inermis (honey locust)	oval/ spreading	60(18) × 20(6)	fast	light	moderate	early	late	4–9	sun-part shade/dry-wet soils
Gymnocladus dioica (Kentucky coffeetree)	oval	60(18) × 40(12)	slow	light	light	average	average	4–8	sun/wide variety of soils
Lagerstroemia indica (crepe myrtle)	vase	20(6) × 15(4)	moderate	light	moderate	late	late	7–10	sun/moist soil
Liquidambar styracifiua (sweet gum) select fruitless cultivar	pyramid	80(24) × 40(12)	moderate/fast	moderate	moderate	late	average	5–10	sun/rich, wet, acid soils
Liriodendron tulipifera (tulip poplar)	columnar/oval	80(24) × 40(12)	moderate	moderate	dense	average	average	4–9	sun/moist, fertile soil
Magnolia acuminata (cucumber magnolia)	pyramid/ spreading	80(24) × 70(21)	moderate	light	medium	average	average	4–8	sun/moist, slightly acid soils
Pistacia chinensis (Chinese pistache)	oval/round	40(12) × 40(12)	slow	medium	dense	average	average	8–10	sun/well-drained soil
Platanus x acerifolia (London planetree)	pyramid/ spreading	90(27) × 70(21)	moderate/fast	light	moderate	late	late	4–8	sun/wide variety of soils
Platanus occidentalis (American sycamore)	round	90(27) × 90(27)	moderate/fast	light	moderate	late	late	4–9	sun/moist soils
Populus deltoides (eastern cottonwood), select seedless cultivars	vase	75(23) × 50(15)	fast	light	light	early	early	2–9	sun/moist soil/invasive roots
Prosopis glandulosa (honey mesquite)	spreading	25(8) × 15(4)	fast	light	light	early	late	8–9	sun/dry, alkaline soils
Quercus palustris (pin oak)	pyramid/ columnar	75(23) × 40(12)	moderate	moderate	moderate	early	late	5–10	sun/acid soils
Quercus phellos (willow oak)	round	60(18) × 40(12)	moderate	medium	dense	late	late	6–9	sun/moist, well-drained soils
Robinia pseudoacacia (black locust)	columnar	50(15) × 30(9)	moderate/fast	moderate	moderate	early	late	3–8	sun/wide variety of soils
Tilia cordata (littleleaf linden)	pyramid	50(15) × 40(12)	moderate/slow	moderate	dense	early	late	3–7	sun/wide variety of soils
Zelkova serrata (Japanese zelkova)	vase	70(21) × 20(6)	moderate	light	moderate	average	late	5–8	sun/moist soils

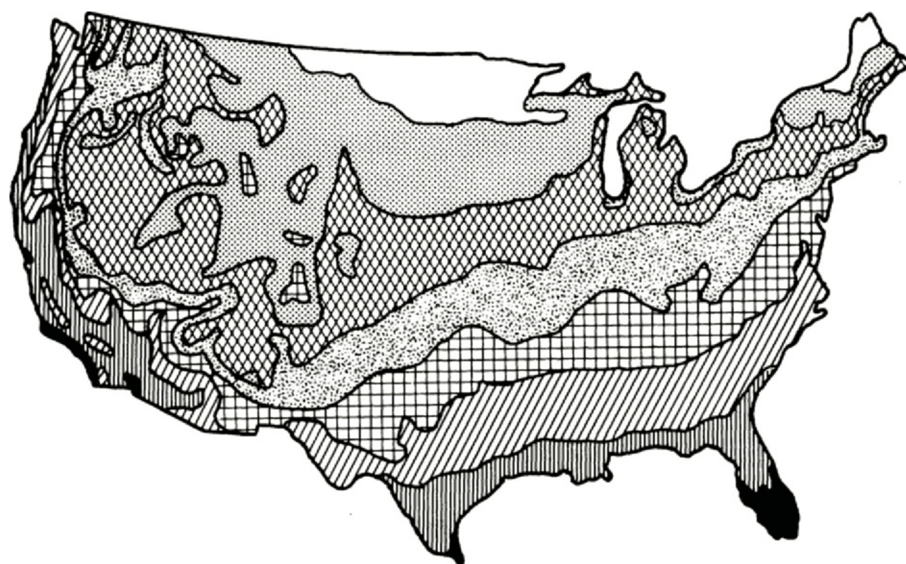


Figure 11.9d This map shows the zones of plant hardiness as listed in Table 11.9. (From Richard Montgomery, *Passive Solar Journal*, Vol. 4 (1), p. 91. Courtesy of the American Solar Energy Society.)

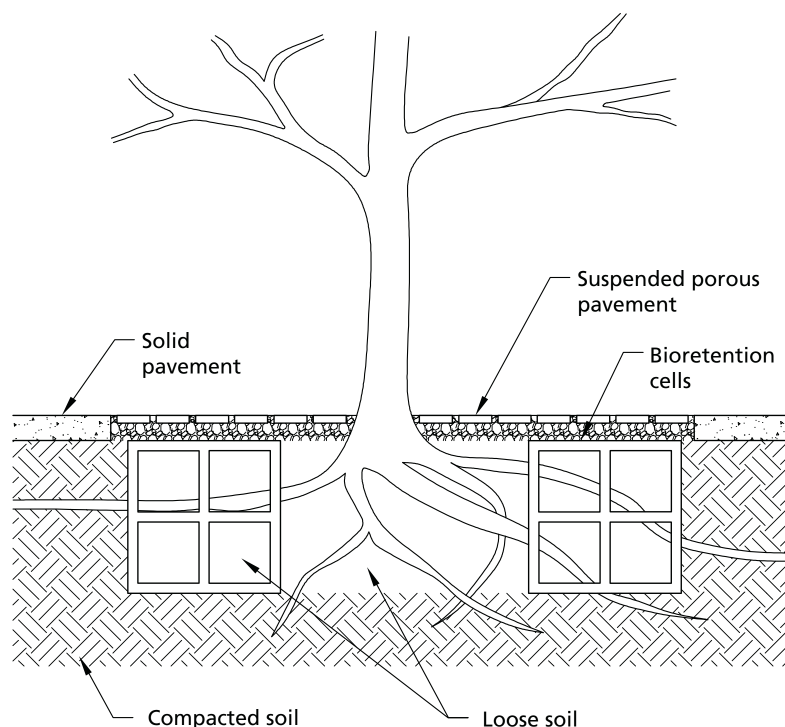


Figure 11.9e Suspended porous pavements by such means as plastic bioretention modules allow urban trees to thrive by providing a large amount of permanently loose and rich soil and a sufficient source of rainwater.

derived from the shade that the plants provide. The shade from a tree is better than the shade from a man-made canopy because the tree does not heat up and reradiate down (Fig. 11.9f). This is the case because of the multiple layers that are ventilated and because the leaves stay cool by the transpiration (evaporation) of water from the leaves. Since only a small amount of the sun's energy is used in photosynthesis, the chemical energy created has little effect on reducing the temperature.

Transpiration cools not only the plant but also the air in contact with the vegetation (Fig. 11.9g). Thus, the cooling load on a building surrounded by lawns will be smaller than on a building surrounded by asphalt or concrete. Trees are even more effective than grass in providing comfort. They provide shade, and unlike grass, their evaporative cooling occurs high above the ground and, therefore, does not much raise the humidity at ground level.

During the summer, grassy areas are superior to paved areas not only during the day but also at night. Because of the high surface temperatures and good conductivity of pavement, large amounts of heat are stored during the day. Consequently, in the evening and all night long, the paved areas will be much warmer than grassy areas. Using large amounts of water to achieve cooling, however, is not the answer in the dry Southwest, nor even in the Southeast, which is also experiencing water shortages. For example, Georgia, Alabama, and Florida are in the courts fighting over the water in the Chattahoochee River. It is becoming increasingly important to avoid using water-guzzling plants in drier areas such as the Southwest. Instead, use a xeriscape design, which is landscaping that saves water and energy. Incidentally, the word "xeriscape" has the same Greek root as "Xerox," which refers to a "dry" process.

Usually the best plants to use are native varieties that have adapted to the local climate, soil, and pathogens. Thus, less water, fertilizer, and chemicals are needed for healthy plant growth. It is not unrealistic to expect a reduction of up to 50 percent in the cooling load when an envelope-dominated building is effectively shaded by plants. A 60 percent reduction in the use of electricity was realized in a Florida school when plants shaded the walls and windows. In another experiment, the temperature inside a mobile home was reduced 20°F (11°C) when it was well shaded by plants.

At night, trees work against natural cooling by blocking long-wave radiation. There will be more radiant cooling in an open field than under a canopy of trees (Fig. 11.9h). Consequently, the diurnal temperature range is much smaller under trees than in an open field, and

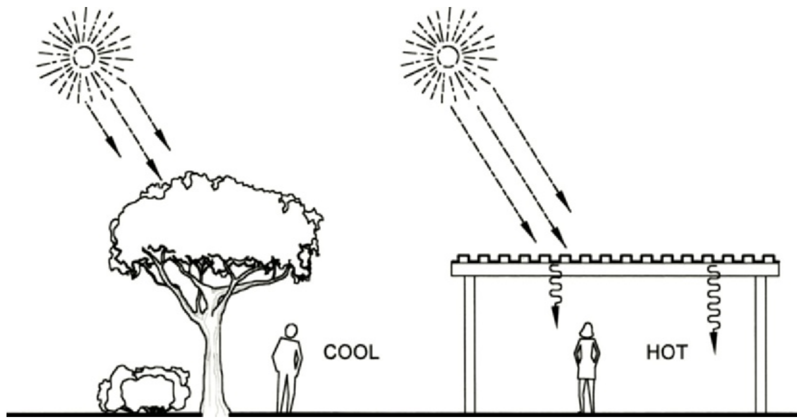


Figure 11.9f Shade from trees is especially effective because trees do not get hot and reradiate heat (long-wave infrared), as do most man-made shade structures. Trees cool themselves by transpiration.

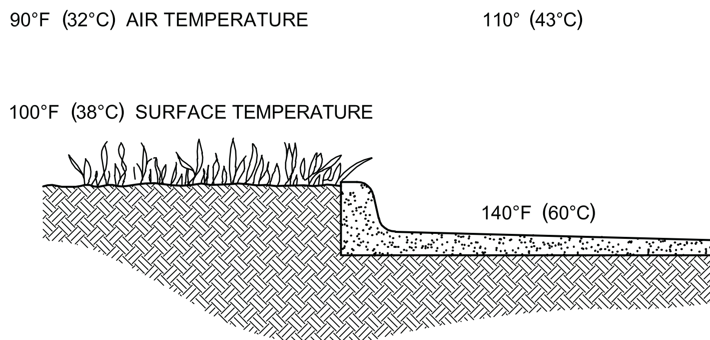


Figure 11.9g Since air is heated by contact with the ground, the air over asphalt is much hotter than the air over grass. On some days, the temperature of asphalt can reach 160°F (71°C). The asphalt also stores more heat, making nights less comfortable in summer.

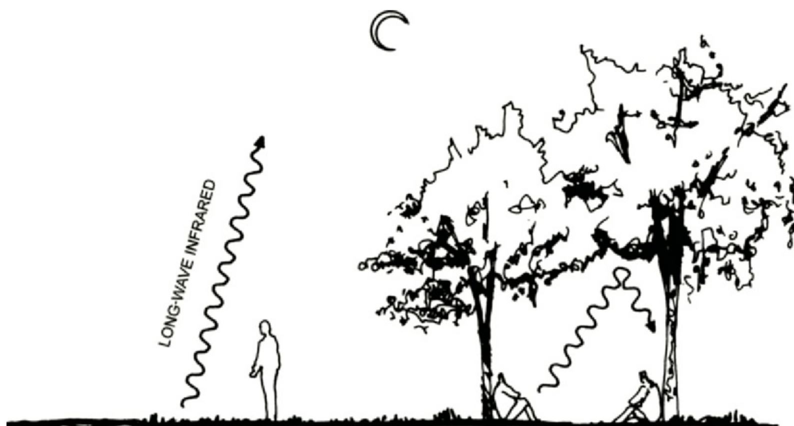


Figure 11.9h At night, it is warmer under trees than in an open field because the trees block the outgoing heat radiation.



Figure 11.9i Plants can soften and diffuse daylight and reduce the glare from the bright sky and light-colored surfaces. Apartment complex in Vienna designed by F. Hundertwasser.

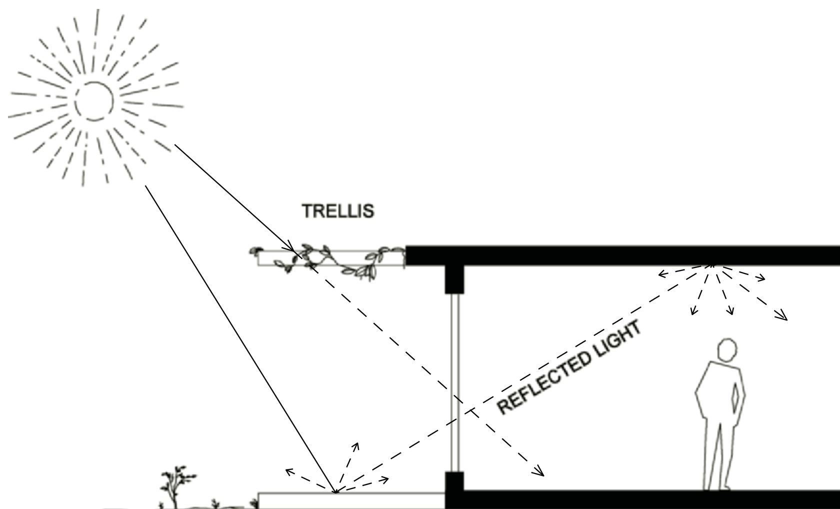


Figure 11.9j Quality daylight can be achieved by blocking direct sunlight while encouraging reflected sunlight.

radiant cooling at night is not feasible under trees.

Plants can also improve the quality of daylight entering through windows. Direct sunlight can be scattered and reduced in intensity, while the glare from the bright sky can be moderated by plants (Fig. 11.9i). Vines across the windows or trees farther away can have the same beneficial effect. Since light reflected off the ground penetrates deeper into a building than direct light, it is sometimes desirable not to have vegetation right outside a window on the ground (Fig. 11.9j). See Chapter 13 for a detailed discussion on daylighting.

Vegetated green roofs have become very popular, but for reducing the cooling load on a building, vegetated green walls are often more effective. In multistory buildings, the wall area is usually larger than the roof area, and in high-rise buildings the wall area is always much larger than the roof area. In addition, the roof of very high buildings is usually covered with cooling towers. Thus, in many buildings, vegetated walls can reduce cooling loads much more than vegetated roofs. Plants are most helpful on the east and west walls, which are exposed mostly to the summer sun. The north wall needs the least shading, and the south wall's shading needs depend on the building type and climate. The plants can also help shade the east and west windows. When shading windows, hanging plants are best because they mainly shade the upper window while preserving much of the view straight out and down. Shading south windows with plants on buildings that need winter heat is a challenge because even deciduous plants shade a great deal. For such buildings, a movable system such as awnings may be a better option.

By far the easiest way to create vegetated walls is to use either climbing vines or plants hanging from planters, especially if there are balconies to support the planters. Most modern vegetated walls use stainless steel cables or mesh to support the vines. Bio walls with vertical planters are significantly different and are not recommended for shading most buildings, because of their expense, complexity, and high maintenance requirements. Bio walls are more suitable for indoor walls and outdoor walls close to the ground where their aesthetic value can be fully appreciated.

There is no doubt that the proper choice and positioning of plants can greatly improve the microclimate

of a site. However, choosing a specific plant can be difficult because of the tremendous variety that exists and because of the specific needs of plants, such as minimum and maximum safe temperatures, rainfall, exposure to sun, and soil type. For these reasons, advice should be obtained from such sources as local nurseries, agricultural extension agents, state foresters, and landscape architects.

Choose plants suited to the local environment!

11.10 VEGETATED ROOFS

Greek soldiers returning from Babylon in 500 B.C. reported that the city was overflowing with green plants and flowers. They said that plants were hanging everywhere from the roofs of houses and temples. If the Hanging Gardens could be created in Babylon in 600 B.C., then surely we could do the same today. Our cities would be more pleasant to live in if the roofs were mostly covered with plants (Fig. 11.10a). Fortunately, green roofs are becoming very popular because they reduce the cooling load on buildings, reduce the heat island effect in cities, reduce storm-water runoff, reduce noise transmission, reduce air pollutants that normally collect on roofs and are then flushed into streams, extend the life of roof membranes, create wildlife habitat, and make buildings and cities more humane (Fig. 11.10b).

Although roofs covered with plants are often called "green" roofs, they are now better known as **vegetated roofs**, because white roofs are also green. The worst example of



Figure 11.10a The Hanging Gardens of Babylon should be an inspiration to not only artists but also city planners, urban designers, and architects.

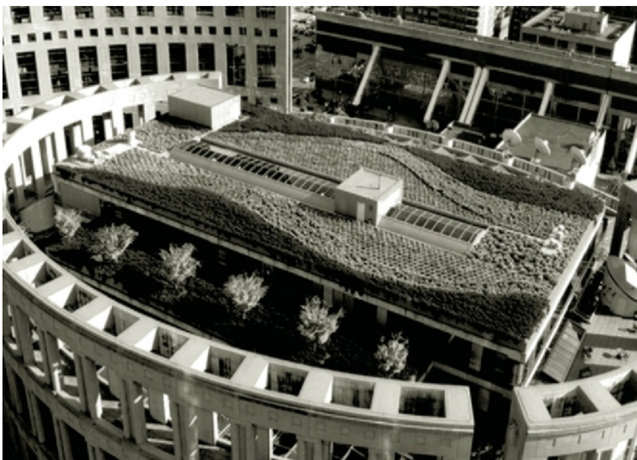


Figure 11.10b Although the thermal benefits of vegetated roofs are greatest in hot climates, their many other benefits also make them popular in cold climates. Vancouver City Library, British Columbia, Canada. Architects: Moshe Safdie & Associates. Area of green roof: 8000 ft^2 (720 m^2) in 2002. (Courtesy of American Hydrotech Inc.)

"greenwash" that the author has seen are flat roofs coated with green paint. Remember:

White is the greenest color!

If the vegetated roof is designed to grow only grass and small flowers, the soil can be as little as 2 in. (5 cm) thick. Such a vegetated roof is called extensive, while an intensive roof will have about 6 in. (15 cm) of soil to grow larger flowers and small shrubs. If large shrubs or small trees are desired, then deeper pockets of soil must be provided, but such pockets would be a significant load and should be placed over or near columns and bearing walls. Extensive vegetated roofs add a dead weight as low as 13 lb/ft^2 (63 kg/m^2), while intensive roofs weigh about 40 lb/ft^2 (200 kg/m^2). These dead weights are much less than normal soil weights would suggest, because the planting medium that is typically used consists of 80 percent lightweight aggregates such as perlite, vermiculite, and expanded shale. The remaining 20 percent consists of highly water-absorbing material, which could be organic.

Besides the soil, there are several other important parts to a vegetated roof system (Fig. 11.10c). To thrive, plants need just the right amount of water—both too much and too little are bad. Thus, a drainage/retention layer regulates the moisture content by draining excess water. Below that layer are the root barrier and waterproof membranes that protect the roof insulation. It must be emphasized that vegetated roofs need just as much insulation as regular roofs for reducing heat loss in the winter. For backup, there may be another waterproof membrane under the insulation. Although other systems vary somewhat, they all need to address the same problems. One alternative system consists of modular trays that come ready from the nursery to place on the roof membrane (Figs. 11.10d and 11.10e).

One of the great advantages of vegetated roofs is the reduction of storm-water runoff, which has

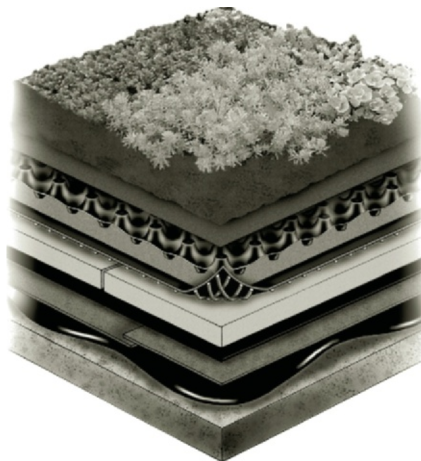


Figure 11.10c An extensive vegetated roof system for growing grass and small flowers is shown. Many layers are required to perform all the functions of a successful green roof. An intensive system would have more growing medium (soil) to allow larger plants to grow. (Courtesy of American Hydrotech Inc.)



Figure 11.10d Some vegetated roofs are made of modular trays that come with plants from the nursery and are placed on conventional roof membranes. (Courtesy of GreenGrid.)



Figure 11.10e This roof garden, or intensive vegetated roof, is made from modular trays. Taller plants that need more soil have deeper trays. (Courtesy of GreenGrid.)

both economic and environmental benefits. In nature, rainwater gets absorbed by the soil, and whatever does not evaporate or is not used by plants makes its way slowly to streams. Meanwhile, the nonporous surfaces of cities force storm water to surge into streams, causing erosion and poor water quality. Vegetated roofs, however, absorb much of the rainfall, which is then used by the plants, while the rest is discharged into the storm-water system, but with a delay. Thus, the building's discharge is greatly delayed and diminished, both protecting the local ecology and requiring a smaller and cheaper municipal storm-water drainage system.

The other important benefit of vegetated roofs is the reduced summer cooling load. Although wet soil is a poor insulator, the **transpiration** from the plants and **evaporation** from the soil (**evapotranspiration** for the combination) cool the plants, soil, and contiguous air. Thus, the cooling load on the building is greatly reduced. In a single-story building, the cooling load can be reduced as much as 30 percent. Vegetated roofs also reduce the urban heat island effect.

Because the wet soil does not reduce heat loss, the insulation required in the winter will be the same as for a building with no vegetated green roof. Thus, the thermal benefits of green roofs are greatest for buildings in hot climates and cities in most climates. However, vegetated roofs are also popular in colder climates because of the many other benefits mentioned before. They are especially desirable in special situations, such as proximity to airports or noisy highways, for their acoustical benefit. A properly designed vegetated roof can also be economical for several reasons, including the 100–500 percent extension on the life of the roof membrane. And if all of these benefits are not convincing enough, one LEED point can be earned by having at least 50 percent of a commercial roof vegetated.

Of course, the design of roof gardens will vary with climate. A design of a roof garden for a northern climate might include high parapet walls on the north, east, and west facades to deflect the cold winds. An open or glass railing on the south side would allow the winter sun to enter (Fig.

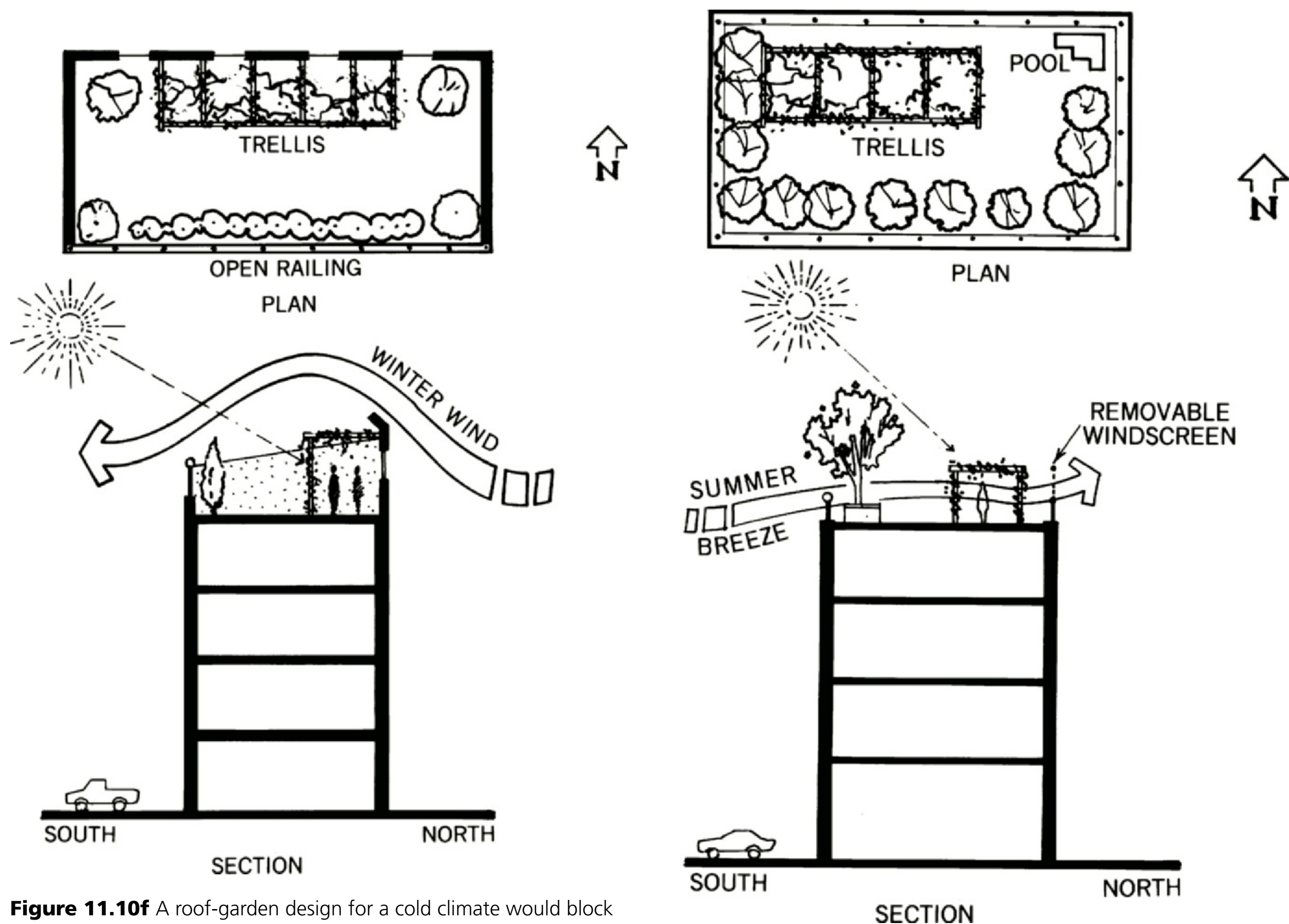


Figure 11.10f A roof-garden design for a cold climate would block the cold northern winds while allowing the winter sun to enter. In hot and dry climates, the garden needs to be protected from drying winds from all directions.

Figure 11.10g A roof-garden design for a hot and humid climate would maximize natural ventilation.

11.10f). A roof garden in a hot and humid climate, on the other hand, would be open to cooling breezes and be well shaded by trees, trellises, etc. (Fig. 11.10g). In hot and dry climates, gardens are typically surrounded by walls to keep out the hot wind. Thus, such gardens would be more like the design shown in Figure 11.10f.

Rules for Vegetated Roofs

1. Use only quality vegetated roof systems to prevent water damage to the building.
2. Account for the higher dead load. Deep soil pockets for trees should be placed near vertical supports and not near the middle of long spans.
3. Use the same amount of insulation as if the roof were not vegetated.
4. Consider making the vegetated roof an accessible roof garden.

Vegetated roofs are most appropriate in cities and in hot climates!

11.11 LAWNS

Lawns became popular in eighteenth-century England, where rich landowners wanted vistas and "improved-upon nature." Their lawns were mowed mainly by sheep, cattle, and horses because cutting short grass with a scythe was expensive. To eliminate the need for grazing animals, the first mechanical lawn mower was patented in 1830. In the United States, lawns did not become popular until after the Civil War because they were a luxury. Although lawns are very practical for sports, for children to play, and for picnicking, most lawns are purely for show (aesthetic and status reasons). Presently, the area of lawns in the United States is about equal to the area of Pennsylvania.

Unfortunately, lawns have a high economic and environmental cost. Mowing lawns accounts for about 5 percent of U.S. air pollution and much of the noise pollution, especially on days of rest. Lawns consume about 30 percent of drinking water in the eastern United States and about 60 percent in the West. Because of the desire to have a lawn look as perfect as Astroturf, the resultant use of fertilizer, herbicide, and insecticide pollutes the environment. Any deviant like the beautiful and beneficial dandelion is considered an evil pest to be exterminated at any cost.

Fortunately, there are good alternatives. Maintaining or restoring the native natural environment is the best option. It will require little, if any, watering, fertilizer, pesticide, or herbicide. If views and vistas are desired, then native grasses and flowers can be planted. Of course, lawns for sports, play, and picnicking should be kept. In addition, when a decorative lawn is desired, only small patches should be used. The resulting landscaping will be less expensive, healthier for both wildlife and humans, more beautiful than the present monoculture lawns, and more sustainable.

11.12 LANDSCAPING

The concepts discussed above can now be combined into landscaping techniques that can reduce heating and cooling costs as much as 25 percent. Figure 11.12a illustrates the general tree-planting logic for most of the country, while Figures 11.12b–11.12e present landscaping techniques appropriate for four different climates (temperate, very cold, hot and dry, and hot and humid).

When trees are not available to shade the east, west, and north windows, high bushes or a vine-covered trellis can be used. Bushes can shade windows just like vertical fins, which were discussed in Chapter 9. And, like fins, shrubs should extend above the windows and be fairly deep

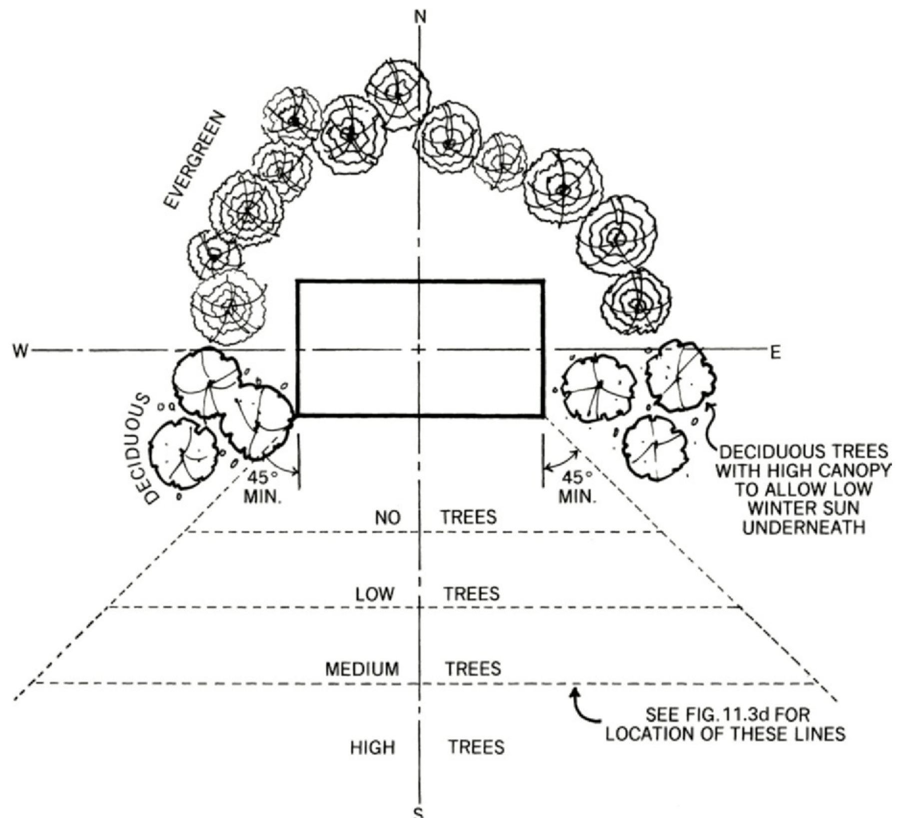


Figure 11.12a The logic for tree planting around a building includes shade trees on the east and west, wind breaks on the north, and open fields on the south-facing sides.

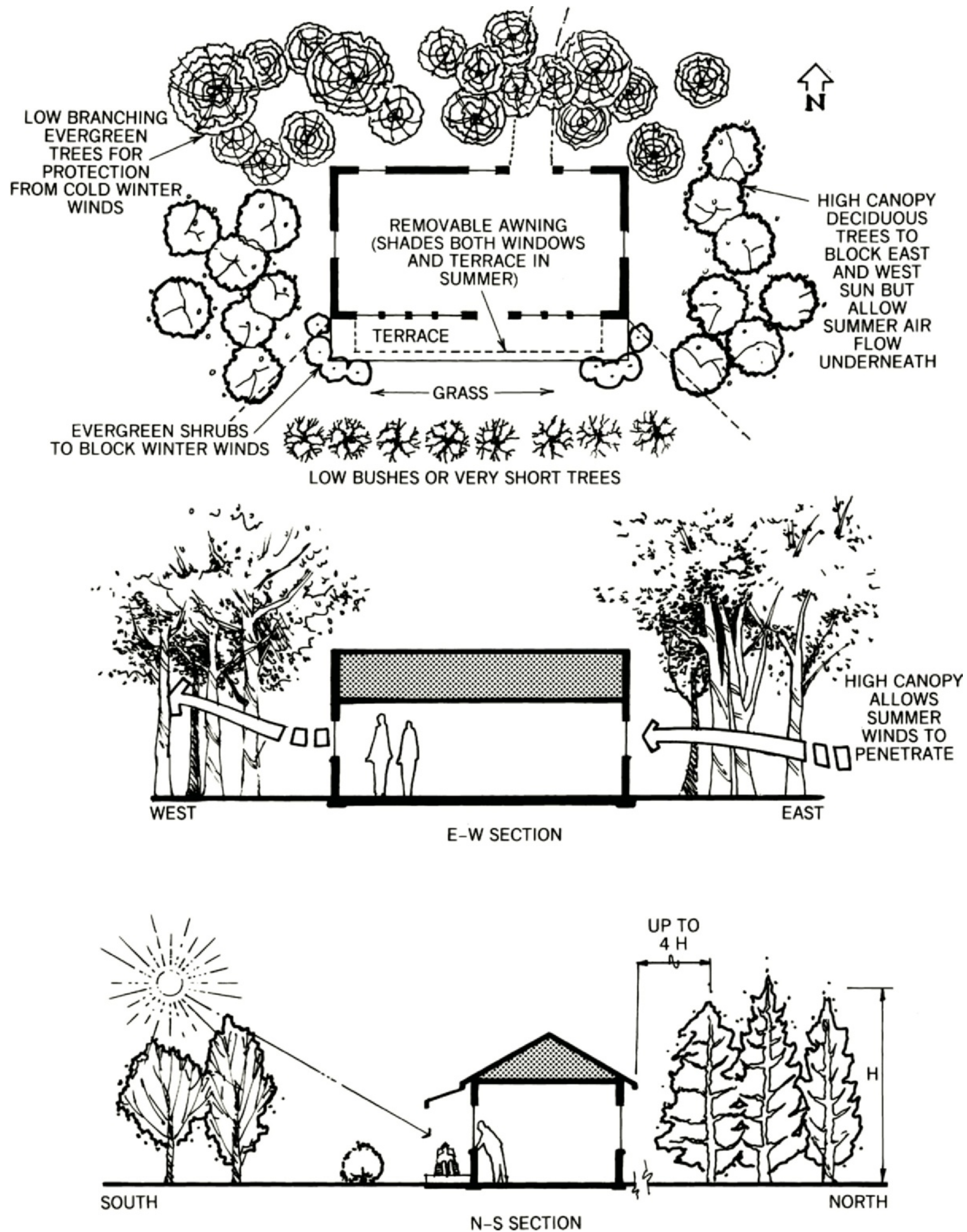


Figure 11.12b Landscaping techniques for a temperate climate. The windbreak on the north side of the building should be no farther away than four times its height. Contrary to their name, temperate climates are hot in the summer and cold in the winter.

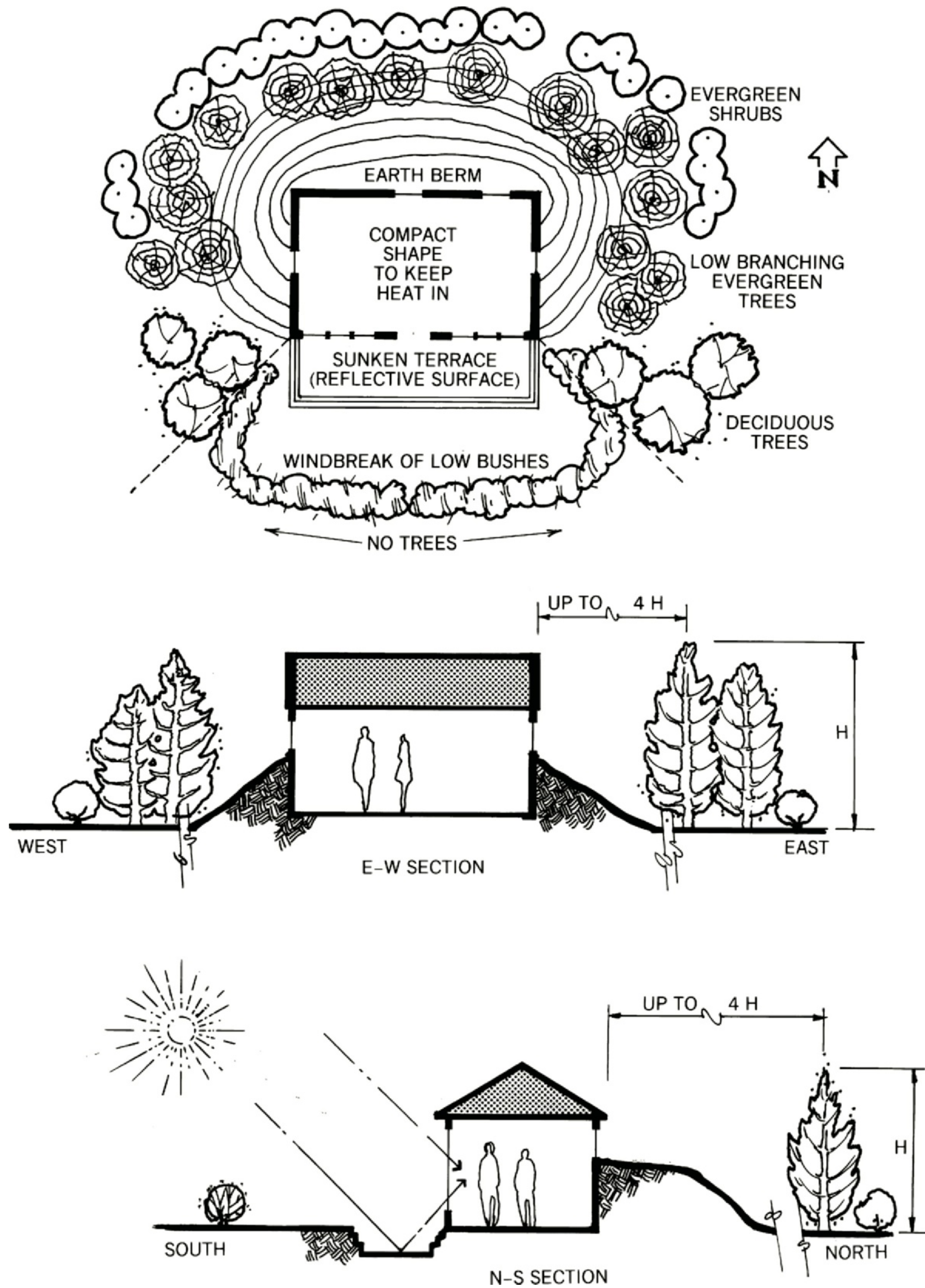


Figure 11.12c Landscaping techniques for very cold climates.

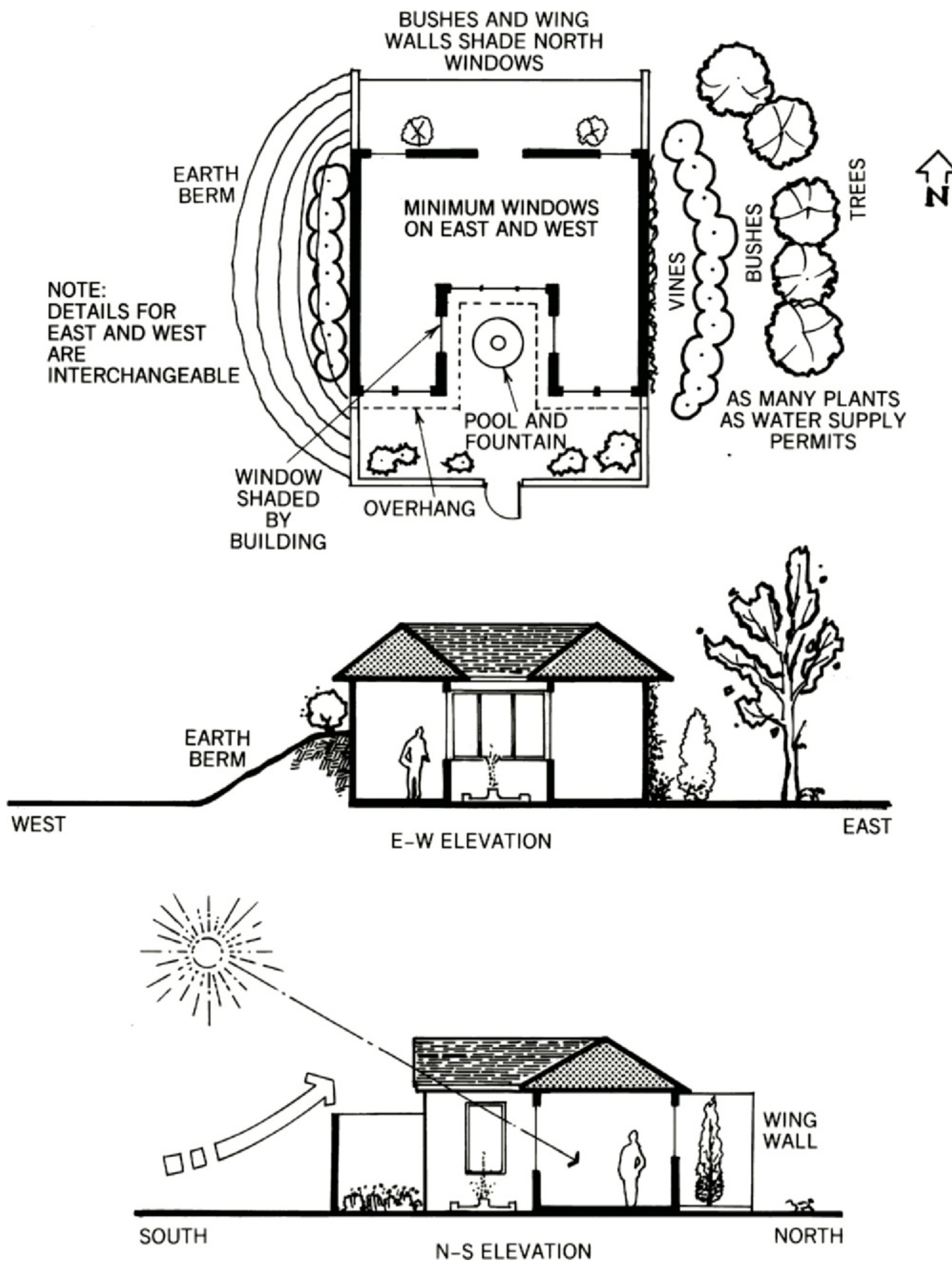


Figure 11.12d Landscaping techniques for hot and dry climates. Courtyards and garden walls keep out the hot winds and conserve cool, moist air.

(Fig. 11.12f). A vertical vine-covered trellis is very effective on east and west facades, while a horizontal trellis can be used on any orientation (Fig. 11.12g).

Outdoor shading structures, such as trellises, pergolas, and arbors, are described in Chapter 9, Figures 9.16f–9.16h. Other functional landscaping elements include allées, pleached allées, and hedgerows (Fig. 11.12h). **Allées** are garden walks bordered with shrubs and trees; they primarily control sight lines but can also be used for providing shade and/or to control air movement. In **pleached allées**, closely spaced trees or tall shrubs are intertwined and pruned to form a tunnel-like structure. Not only do these features effectively frame views, they also create cool, shady walkways.

The term "**hedgerow**" refers to a row of bushes, shrubs, or trees forming a hedge. Depending on the orientation, such hedges can be used for shading, wind protection, or wind funneling.

As mentioned before, pools of water and especially fountains can be used to cool the air. However, if these features are used in hot and humid climates, they should be placed downwind to avoid adding more humidity to the air. In very dry climates, the water should be placed in a sheltered courtyard to

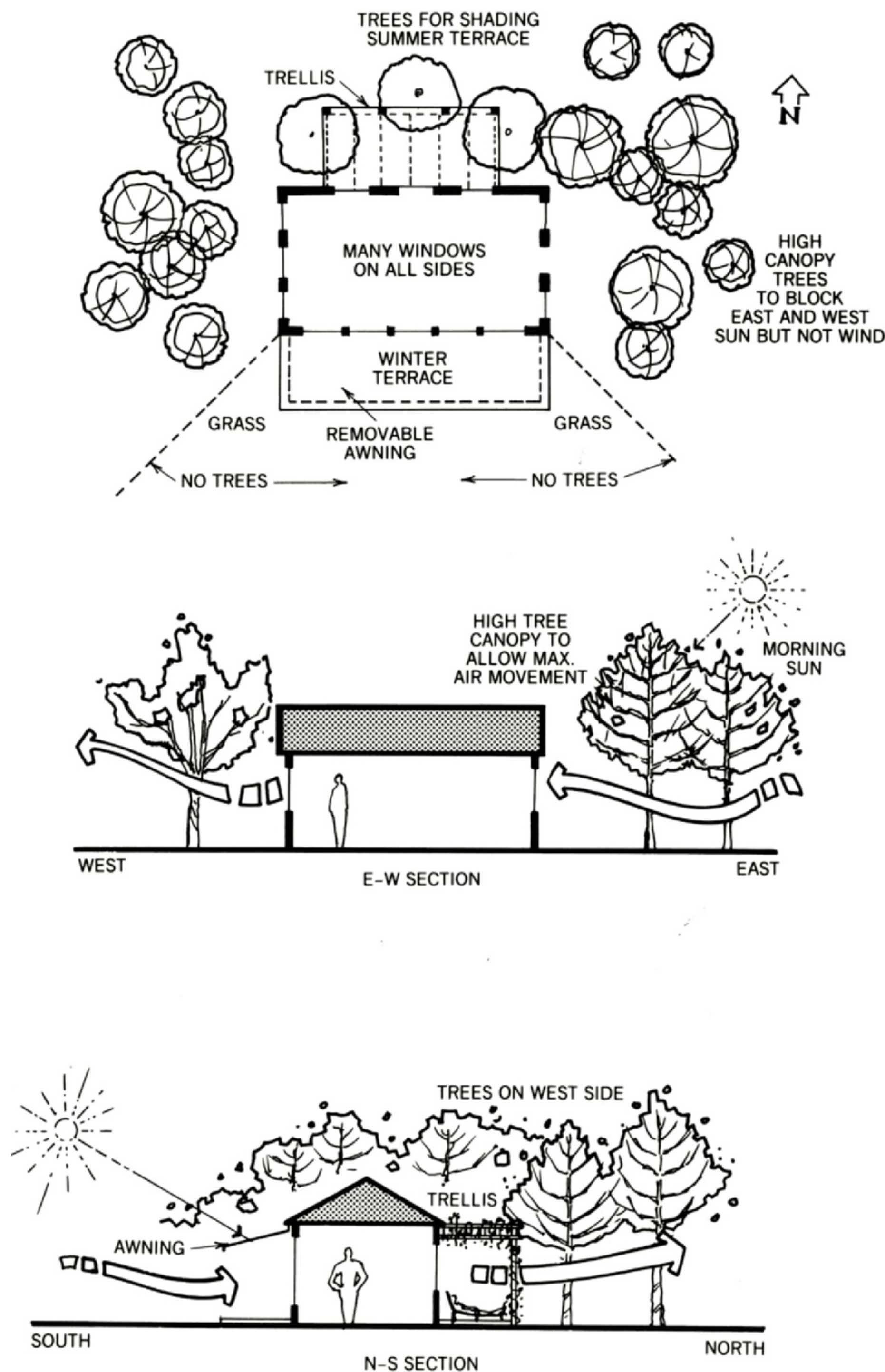


Figure 11.12e Landscaping techniques for hot and humid climates. Use high-canopy trees to maximize air movement near the ground.

preserve the cooled air. Unless the water is chlorinated, a healthy ecosystem should be created to keep the water clean. As waterfalls or fountains cool the air, they also oxygenate the water for fish and snails, which are required to control mosquitoes and algae growth. In very hot climates, the water should be shaded to prevent overheating and excessive algae growth (Fig. 11.12i). A natural black dye added to the water will also prevent algae growth. The water should also circulate and not become stagnant.

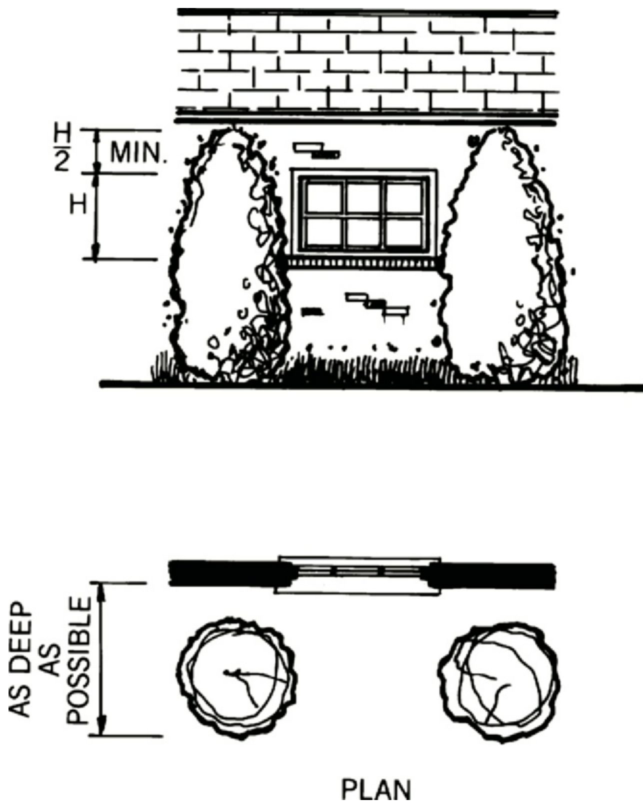


Figure 11.12f Bushes can act as vertical fins to block the low sun on north facades. On east and west windows, only the bush on the north side should be used if winters are cold.

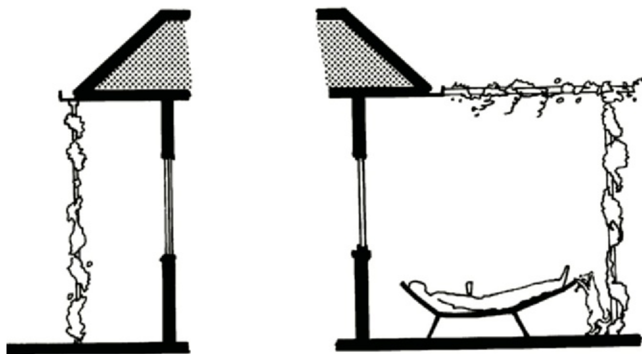


Figure 11.12g Vine-covered trellises are effective devices for creating shade. A newly planted vine will provide shade much sooner than a newly planted tree.

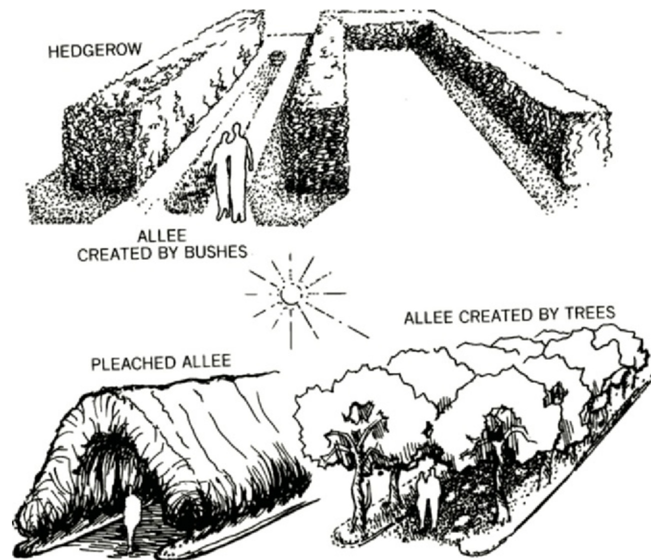


Figure 11.12h Landscaping elements for creating shade and/or controlling air movement include allées, pleached allées, and hedgerows.



Figure 11.12i Waterfalls, fountains, and pools can cool the air in all but very humid climates. If the climate is very hot, the water should be shaded by trees, bushes, water plants, etc.

11.13 COMMUNITY DESIGN

Community planning can either promote or hinder the sustainable design of each lot. Outside of Phoenix, Arizona, is a place called Sun City. Although the name might suggest a place in harmony with the sun, the street layout shows a total disregard for sun angles (Fig. 11.13a). On circular streets, every building has a different orientation. Only two buildings on each street have the ideal east–west orientation, where the small facades face east and west and where shading from neighbors is at a maximum. Thus Sun City might be better named Anti-Solar Responsive Design City.

A quite different approach is illustrated in the street plan of Village



Figure 11.13a With a circular street layout, every building has a different orientation, and only a small number have the ideal east–west orientation.

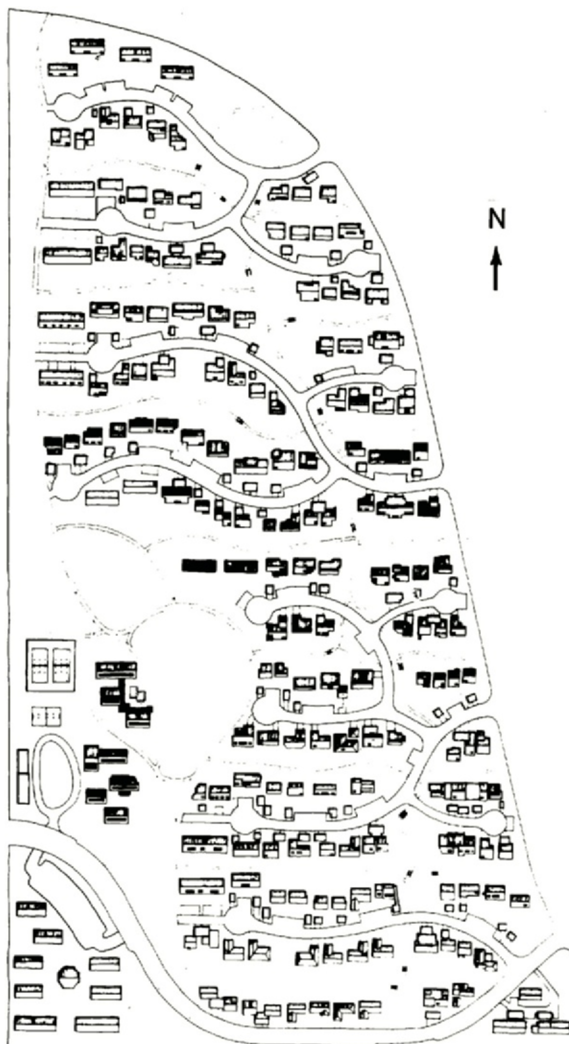


Figure 11.13b In the community of Village Homes in Davis, California, most streets run east–west to promote winter solar access and summer shading. (From *Village Homes' Solar House Design*, by David Bainbridge, Judy Corbett, John Hofacre. Rodale Press, 1979. © Michael N. Corbett.)

Homes in Davis, California (Fig. 11.13b). Although the site runs north–south, the streets all run east–west, which allows every building, without exception, to have the ideal orientation. Bicycle and pedestrian paths are included in part to reduce the use of automobiles (Fig. 11.13c). Studies have shown that houses in Village Homes use on average about half of the energy required by comparable nonsolar buildings in the same area. In addition, these houses tend to be more comfortable, desirable, and economical. Their success and popularity are indicated by their high resale value.

As much as possible, Village Homes encourages employment opportunities within the community. Tremendous amounts of energy and time could be saved if people did not have to commute so much. Fortunately, studies show a clear trend in the United States of an increasing demand for walkable neighborhoods and a decreasing demand for the traditional low-density suburbs.

The existence of communities such as Village Homes is in part due to the zoning technique called **planned unit development (PUD)**. PUD provisions allow for modification of lot size, shape, and placement

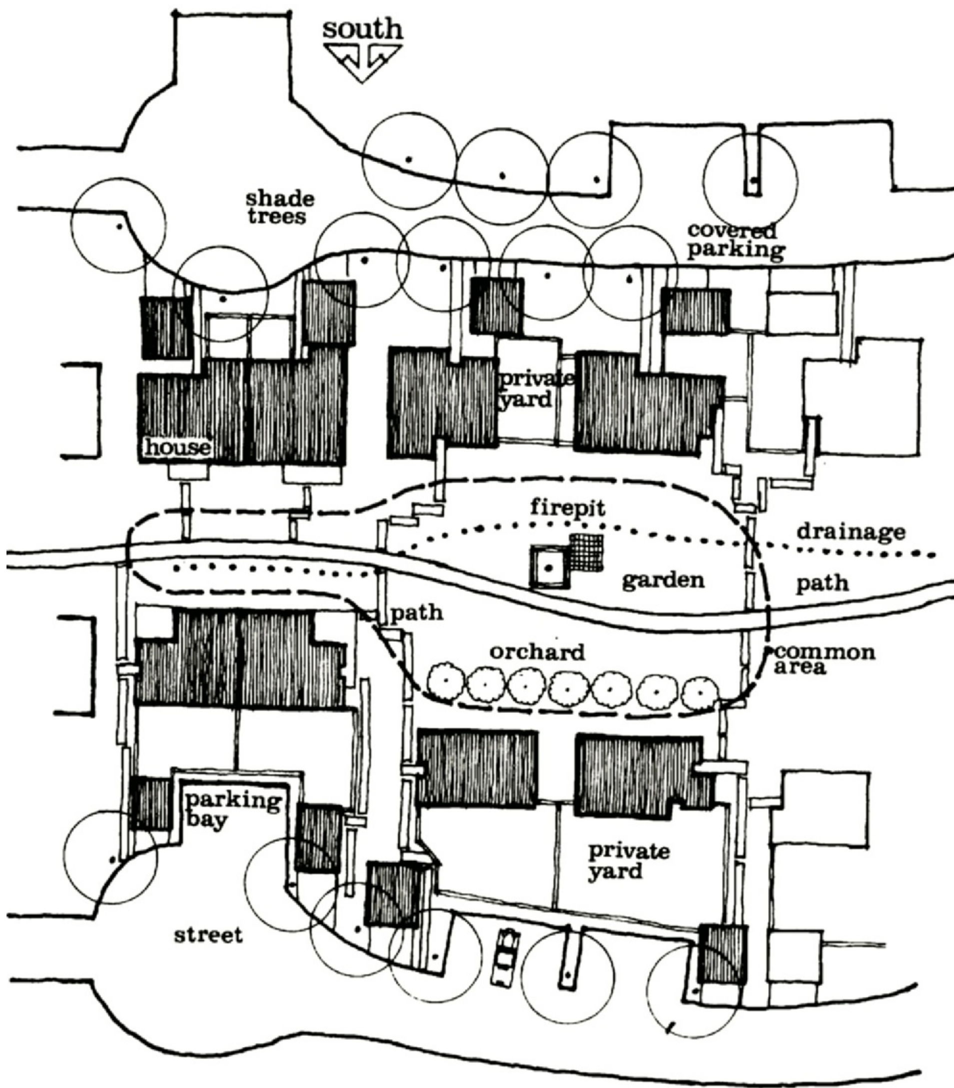


Figure 11.13c Cluster housing saves land and energy. The saved land is used for pedestrian/bicycle paths, recreation, vegetable gardens, and orchards. (From *Village Homes' Solar House Design*, by David Bainbridge, Judy Corbett, John Hofacre. Rodale Press, 1979 © John C. Hofacre.)

for increasing siting flexibility (Fig. 11.13c). Thus, solar access and community open land for playing fields, community gardens, and community orchards can be maximized.

Besides creating more sustainable suburban designs, cities could be built as attractive alternatives to suburban living. Although there are many reasons to live in the suburbs, the presence of a great amount of greenery is a major attraction. Roof gardens, green balconies, small private gardens, large public gardens, and trees and flowers along all streets could make a city not only cooler and healthier but also an attractive alternative to suburban living.

Although most people seem to agree that **sprawl** is undesirable, what is actually being done suggests otherwise. What is presented as **smart growth** is often **greenwash**. The basic causes of sprawl are usually not addressed. At least 50 percent of sprawl is the result of population growth. The rest of it is caused by various factors such as a desire to live in nature, which present cities don't provide, and a desire to buy larger houses (i.e., growing affluence). Thus, we come back to Paul Ehrlich's equation, which was described in Section 2.5:

$$I = P \times A \times T$$

To reduce the impact on the environment (I), we need to reduce population growth (P), have a higher quality of life rather than growing affluence (A), and make technology (T) work for the environment rather than against it. Thus, if we need to stop or reduce the growth of population and affluence, the term "smart growth" is an oxymoron.

11.14 COOLING OUR COMMUNITIES

Urban areas are much hotter than the rural areas around them. Figure 5.3e and Colorplate 34 show the

heat-island effect caused mainly by the excessive absorption of solar energy. The darker the surfaces, the more heat is absorbed, with black roofs reaching a temperature of 160°F (71°C). For every 1°F (0.6°C) increase in urban temperature, electricity use increases 2 percent and the production of smog increases 3 percent. Significantly cooler communities are possible by using light-colored materials for roofs, walls, and especially paved surfaces. Materials should have a very high albedo (a factor that measures the reflectivity of solar radiation). A surface with an albedo of 1 reflects all radiation, while a surface with an albedo of 0 absorbs all radiation. Black roofs are especially bad because they heat both the buildings and the urban area.

Certain paved areas, such as driveways and parking areas, can be made not only of light-colored materials such as concrete but also of special blocks that allow grass to grow in the openings. All plants cool by transpiration, and trees have the double benefit of creating shade, while the transpiration occurs high above the ground where the increase in humidity will blow away faster. Significant comfort and energy savings are possible from ordinances requiring the use of light colors, the planting of trees, vegetated roofs, and other plant covers.

Much excellent information is available on how to cool our communities, and many organizations have been set up to promote this goal. See especially:

1. www.coolcommunities.org
2. www.nationaltreetrust.org
3. *Cooling Our Communities: A Guidebook on Tree Planting and Light Colored Surfacing*, U.S. Environmental Protection Agency (1992).

11.15 CONCLUSION

Site and community planning can have a tremendous effect on energy consumption. For example, the annual per capita energy use in New York City is about one-half of the U.S. average.

In Davis, California, good planning and building design has resulted in some houses that have achieved 100 percent natural cooling and 80 percent solar heating. Similarly, the Beddington Zero (fossil) Energy Development (BedZED) is an urban development where good planning and building design have resulted in a delightful and truly sustainable community.

Planning decisions made today will be with us for decades, if not centuries. It will be very unfortunate if future interest in solar energy is frustrated by the poor planning decisions made today. It is almost certain that PV electricity, the almost ideal energy source, will become economical in the near future. When that day arrives, some buildings will be able to make much better use of it than others. For architects and others with great aesthetic sensibilities, a world with jury-rigged solar collectors on a multitude of misoriented buildings will be a constant irritation and reminder of lost opportunities. Thus, providing proper orientation and solar access today is critical.

The proper layout of streets, the proper design of building lots, the proper orientation of buildings, and an abundance of nature will not only reward us now but also create a decent legacy for our children and our children's children.

KEY IDEAS OF CHAPTER 11

1. East–west streets offer the best access to the winter sun and the best shading from the summer sun.
2. The solar-access boundary can be used on plans and sections to ensure winter solar access.
3. Shadow patterns can be used on site plans to ensure winter solar access to all buildings.
4. Solar zoning ensures solar access through ordinances.
5. Use physical models as a design tool for ensuring winter solar access and summer shading.
6. Use site features to block the cold winter wind and to funnel in the summer wind.
7. Use plants to block the winter wind and the summer sun.
8. Landscaping that supports the heating, cooling, and lighting of buildings varies with the climate.
9. Because of their many advantages, vegetated roofs are highly recommended.
10. Lawns, which are an environmental liability, should be used only when necessary.
11. Design communities for sustainability. Emphasize east–west streets, and deemphasize the need for automobiles.

References

Heschong, L. "Classrooms and Windows" and "Offices with Windows," 2003. www.h_m_g.com.

Kellert, S. R., and E. O. Wilson. *The Biophilia Hypothesis*. Washington, DC: Island Press, 1993.

McPherson, E. G. *Energy Conserving Site Design*. Waldorf, MD: American Society of Landscape Architects, 1984.

Ulrich, R. S. "View Through Windows May Influence Recovery from Surgery." *Science*, Vol. 24, 920–921 (1984).

Resources

Further Reading

(See Bibliography in back of book for full citations.)

Akbari, H., et al. *Cooling Our Communities: A Guidebook on Tree Planting and Light-Colored Surfacing*.

Boutet, T. S. *Controlling Air Movement: A Manual for Architects and Builders*.

Brown, G. Z., and M. DeKay. *Sun, Wind, and Light: Architectural Design Strategies*, 3rd ed.

Brown, R., and T. Gillespie. *Microclimatic Climate Design: Creating Thermal Comfort and Energy Efficiency*.

Druse, K., and M. Roach. *The Natural Habitat Garden*.

Dunnett, N., and N. Kingsbury. *Planting Green Roofs and Living Walls*.

Earth Pledge. *Green Roofs: Ecological Design and Construction*.

Foster, R. S. *Homeowner's Guide to Landscaping That Saves Energy Dollars*.*

Francis, M. *Village Homes: A Community by Design: Case Studies in Land and Community Design*.

Givoni, B. *Climate Considerations in Building and Urban Design*.

Groesbeck, W., and J. Stiefel. *The Resource Guide to Sustainable Landscapes and Gardens*, 2nd ed.

Hightshoe, G. L. *Native Trees, Shrubs, and Vines for Urban and Rural America: A Planting Design Manual for Environmental Designers*.

Hottes, A. C. *Climbers and Ground Covers, Including a Vast Array of Hardy and Subtropical Vines Which Climb or Creep*.*

Jaffe, M. S., and E. Duncan. *Protecting Solar Access for Residential Development: A Guidebook for Planning Officials*.

Knowles, R. L. *Energy and Form: An Ecological Approach to Urban Growth*

———. *Sun Rhythm Form*.

Kwok, A., and W. Grondzik. *The Green Studio Handbook: Environmental Strategies for Schematic Design*, 2nd ed.

Lehmann, S. *The Principles of Green Urbanism*.

Lyle, J. T. *Design for Human Ecosystems: Landscape, Land Use, and Natural Resources*.

McHarg, I. L. *Design with Nature*.

McPherson, E. G., ed. *Energy Conserving Site Design*.

Moffat, A., and M. Schiler. *Energy-Efficient and Environmental Landscaping*.

———. *Landscape Design that Saves Energy*.*

Norwood, K., and K. Smith. *Rebuilding Community in America: Housing for Ecological Living, Personal Empowerment, and the New Extended Family*.

Ottsen, C. *The Native Plant Primer: Trees, Shrubs, and Wildflowers for Natural Gardens*.

Petit, J., D. Bassert, and C. Kollin. *Building Greener Neighborhoods: Trees as Part of the Plan*, 2nd ed.

Robinette, G. O. *Energy Efficient Site Design*.

Robinette, G. O., and C. McClenon. *Landscape Planning for Energy Conservation*.

Rocky Mountain Institute Staff. *Green Development: Integrating Ecology and Real Estate*.

Tabb, P. *Solar Energy Planning: A Guide to Residential Development*.

U.S. Department of Energy, Office of Project and Facilities Management. *Site Development Planning for Energy Management. Cooling Our Communities: A Guidebook on Tree Planting and Light Colored Surfacing*. U.S. EPA.

U.S. Department of Housing and Urban Development. *Protecting Solar Access for Residential Development*.

Van der Ryn, S., and P. Calthorpe. *Sustainable Communities: A New Design Synthesis for Cities, Suburbs, and Towns*.

Vickery, R. L. *Sharing Architecture*.

Watson, D., and K. Labs. *Climatic Design: Energy Efficient Building Principles and Practices*.

Paper

Knowles, R. L."The Solar Envelope." At www.rcf.usc.edu/~rknowles

*These books have extensive lists of plants that are useful for energy-conscious landscape design.

CHAPTER 12

LIGHTING

More and more, it seems to me, light is the beautifier of the building.
***Frank Lloyd Wright,* The Natural House,**
©Frank Lloyd Wright Foundation, 1958

The design of human environments is, in effect, the design of human sensory experience; all visual design is de facto also lighting design.
***William M. C. Lam,* Perception and Lighting as Formgivers for Architecture**

12.1 INTRODUCTION

The form of a building is known to us primarily by the way it reflects light. Sensitive designers have always understood that what we see is a consequence of both the quality of the physical design and the quality of light falling on it. The ancient Egyptians found that shallow, negative relief created powerful patterns under the very clear, bright, and direct sunlight of Egypt (Fig. 12.1a). The Greeks found that relief sculpture and moldings were well modeled under the somewhat less bright sun of Greece (Fig. 12.1b). The designers of the Gothic cathedrals had to create powerful statements in the cloudy and diffused light of northern Europe. Here, sculpture in the round could be placed in niches and portals and still be seen because of the softness of the shadows (Fig. 12.1c). Most of the sculpture of a Gothic cathedral would disappear in the dark shadows of an Egyptian sun. The quality of light and the quality of architecture are inextricably intertwined.

Sometimes the architect must accept the light as it is and design the form in response to it. At other times, both the form and the light source are under the architect's control. This is true not only for the interior but also for the exterior at night. Thus, the architect creates the visual environment by both molding the material and controlling the lighting.

The following three chapters on lighting present the information required by the designer to create a quality and creative lighting environment. Such an environment includes the lighting necessary for satisfying aesthetic and biological needs, as well as the lighting required to perform certain tasks. Since a quality lighting environment is not achieved by supplying large quantities of light, the emphasis in this book is not on the quantification of light. This chapter explains the basic concepts required for a creative and quality lighting environment, which is achieved primarily through the geometric



Figure 12.1a Low sunken relief is ideal for the very bright and direct sun of Egypt. (Courtesy of the Egyptian Tourist Authority.)



Figure 12.1b High relief is modeled well by the direct sun of Greece.



Figure 12.1c The cloudy and subdued lighting of northern Europe allows highly sculptured forms. Even when the sun does come out, as in this photograph, it is not so intense that details are lost in dark shadows. (Photograph by Nicholas Davis.)

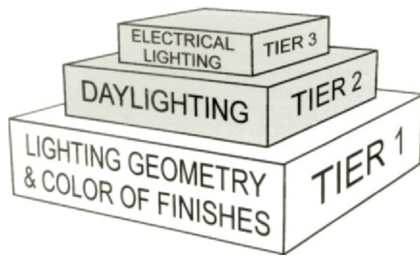


Figure 12.1d High-quality and more sustainable lighting is best achieved via the three-tier design approach. This chapter covers tier one.

manipulation of light and the color of finishes. This aspect of lighting is tier one of the three-tier design approach (Fig. 12.1d). Tier two consists of the natural energy of daylighting, and tier three consists of electric lighting. To design quality lighting, we must start with an understanding of light, vision, and perception.

12.2 LIGHT

Light is defined as that portion of the electromagnetic spectrum to which our eyes are visually sensitive (Fig. 12.2a). In Figure 6.2b, we see the intensity of the solar radiation reaching the earth as a function of wavelength. It is no accident that our eyes have evolved to make use of that portion of the solar radiation that is most intense.

Not all animals are limited to the visible spectrum. Rattlesnakes can see the infrared radiation emitted by a warm-blooded animal. Many insects can see ultraviolet radiation, and to them, flowers look quite different. We can get a notion of how the world looks to them when we see certain materials illuminated by **black light**, which is ultraviolet light just beyond violet. Certain materials **fluoresce** (glow) when exposed to radiation at this wavelength. Ultraviolet radiation of a somewhat shorter wavelength causes our skin to tan or burn. Even shorter ultraviolet radiation is so destructive that it is germicidal and can be used in sterilization (Fig. 12.2a). Although we cannot see beyond the visible spectrum, we can feel infrared radiation on our skin as heat.

Lumen

The rate at which a light source emits light energy is analogous to the rate at which water sprays out of a garden hose (Fig. 12.2b). The power with which light is emitted from a lamp is called **luminous flux** and is measured in **lumens**. We can say that the quantity of light a lamp emits in all directions is indicated by its lumen value (Fig. 12.2c). The same unit is used in the SI system (Table 12.2).

Efficacy

Using efficient lamps saves not only money but also energy and, therefore, the environment. The ratio of light output to energy input is called **efficacy**.

$$\frac{\text{light out}}{\text{energy in}} = \frac{\text{lumens}}{\text{watts}} = \text{efficacy}$$

Thus, the efficacy of the lamps in Figure 12.2c is:

$$\text{Incandescent: } \frac{1740 \text{ lm}}{100 \text{ W}} = 17.4$$

$$\text{Fluorescent: } \frac{7800 \text{ lm}}{100 \text{ W}} = 78$$

$$\text{High pressure sodium: } \frac{9500 \text{ lm}}{100 \text{ W}} = 95$$

Note that fluorescent lamps emit about four times as much light as incandescent lamps for the same amount of electricity.

Candlepower

Lumens, however, do not reveal how the emitted light is distributed. In Figure 12.2d, we see two reflector lamps that give off equal amounts of light (lumens) but with very different distribution patterns. The spot lamp has an intense, narrow beam, while the flood lamp has a much wider beam with less intensity. **Candlepower**, measured in **candelas**, describes the intensity of the beam in any direction. Manufacturers supply candlepower distribution graphs for each of their lighting fixtures (Fig. 12.2e). The SI system uses the term

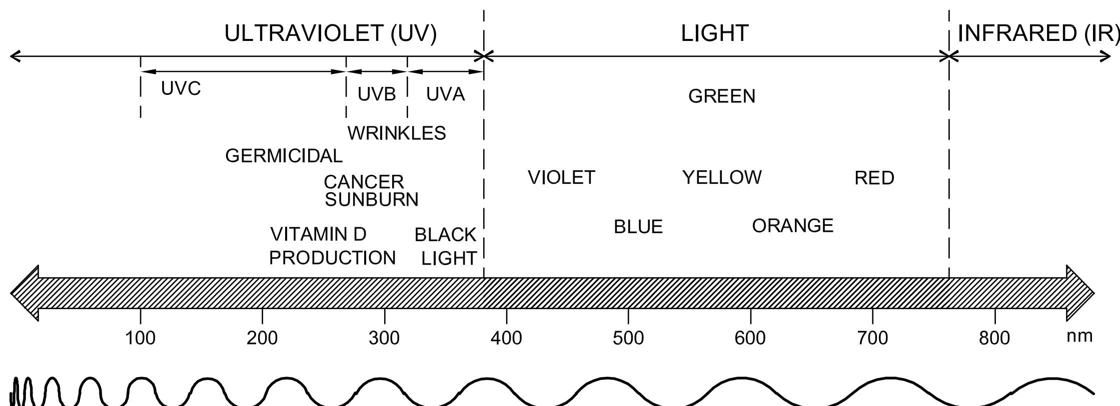


Figure 12.2a Light is only a small part of the electromagnetic spectrum. Light is the radiation to which our eyes are visually sensitive.

Table 12.2 Comparison of the Inch-Pound (I-P) and International System (SI) Lighting Units

	(I-P)	(SI)	Conversion Factor
Supply of light	Lumen (lm)	Lumen (lm)	1
Luminous intensity	Candlepower (cp) or candela (cd)	Candela (cd)	1
Illuminance	Footcandle (fc)	Lux (lx)	1 fc ≈ 10 lx*
Luminance	cd/ft^2	cd/m^2	1 cd/ft^2 ≈ 0.1 cd/m^2*

*Approximations are appropriate because both the eye and most light meters have a high tolerance.



Figure 12.2b The supply of light in lumens is analogous to the supply of water in gallons or liters per minute.

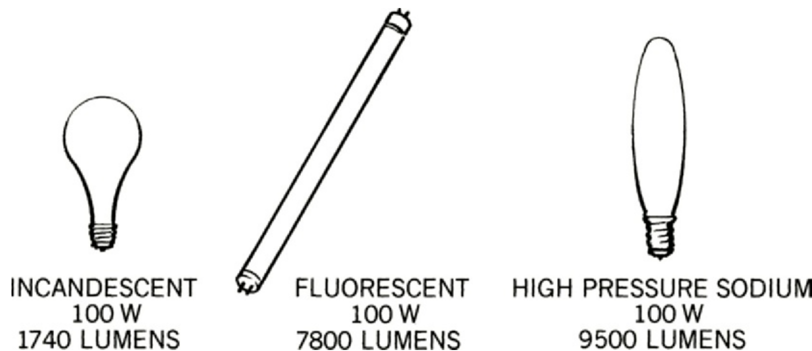


Figure 12.2c The power or rate at which lamps emit light is measured in lumens. Because of large differences in efficiency, lamps of equal wattage can emit very different amounts of light.

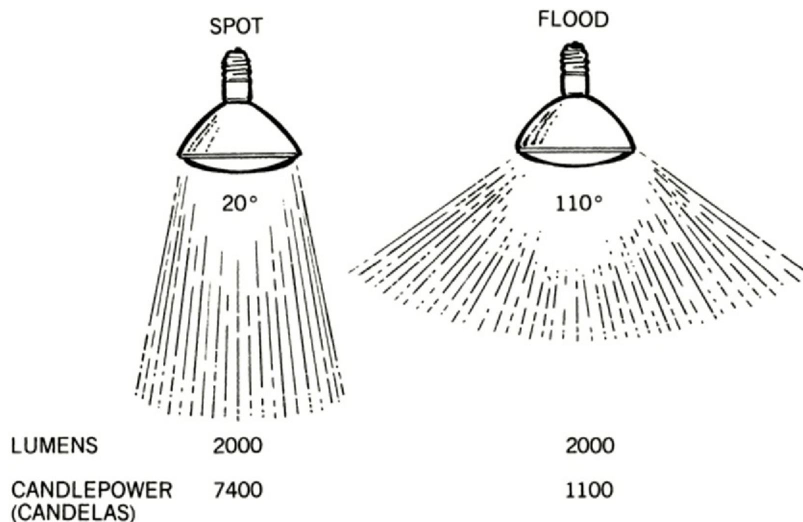


Figure 12.2d Candlepower describes the intensity of a light source. Although both lamps emit the same amount of light (lumens), the intensity and width of the beams are very different. The given candlepower is the average value of the central 10° cone.

candela, and both units have the same magnitude (Table 12.2).

Illuminance

Some of the lumens from a light source will illuminate a particular surface. A meaningful comparison of various illumination schemes is possible only when we compare the light falling on equal areas. **Illuminance** is, therefore, equal to the number of lumens falling on each square foot (meter) of a surface. The unit of illumination is the **footcandle (lux)**. For example, when the light of 80 lumens falls uniformly on a 4 ft^2 table, the illumination of that table is 20 lumens per ft^2, or 20 footcandles (see Fig. 12.2f and Sidebox 12.2 for the SI example). Illumination is measured with footcandle (lux) meters, which are also known as illuminance meters or photometers. Such instruments are available in a wide range of prices.

Brightness/Luminance

The words "**brightness**" and "**luminance**" are closely related. The brightness of an object refers to the perception of a human observer, while the object's luminance refers to the objective measurement of a light meter. The perception of brightness is a function of the object's actual luminance, the adaptation of the eye, and the brightness of adjacent objects. Although the words are interchangeable much of the time, under certain conditions a significant discrepancy exists between what we see (brightness) and what a light meter reads (luminance).

Luminance is the amount of light that is reflected off an object's surface and reaches the eye. The luminance of an object is a function of the illumination; the geometry of the viewer in relation to the light source; the **specularity**, or mirror-like reflection, of the object; and the color, or reflectance, of the object (Fig. 12.2g). Light emitted from glowing or translucent objects is also called **luminance**. Thus, we can talk of the luminance of

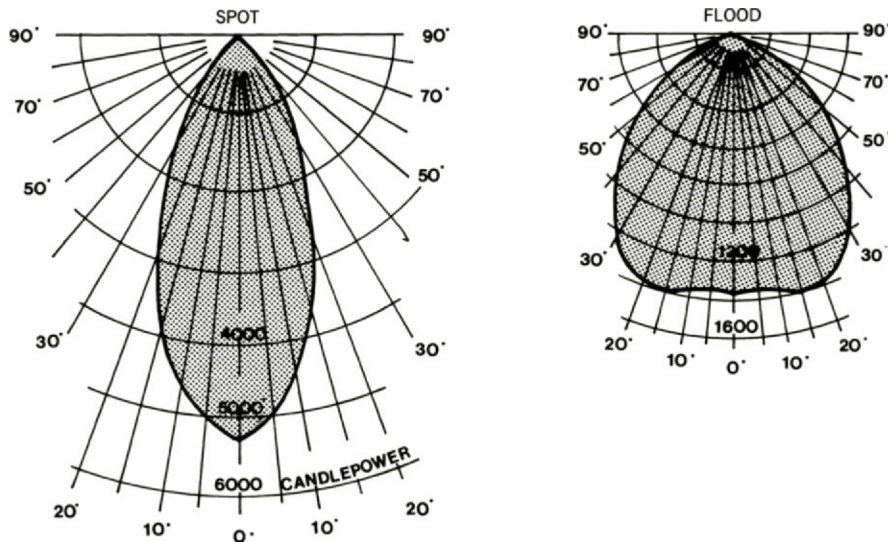


Figure 12.2e Candlepower distribution curves illustrate how light is emitted from lamps and lighting fixtures. In this vertical section, the distance from the center determines the intensity of the light in that direction.

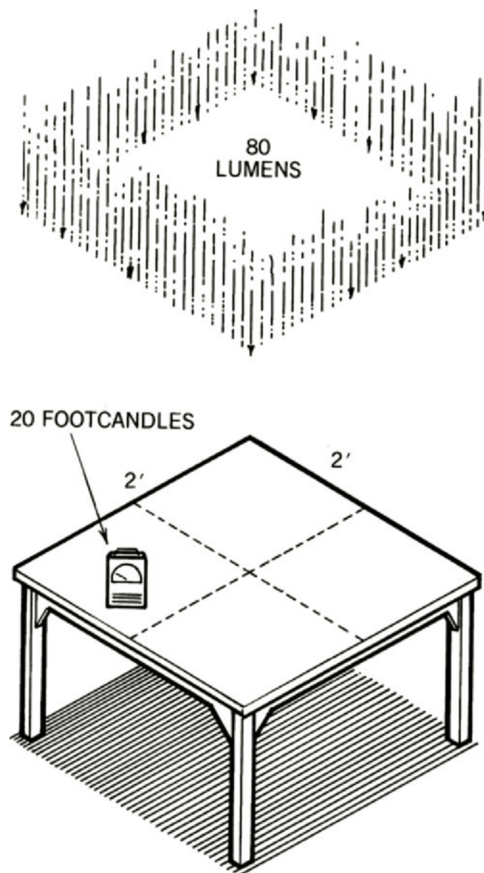


Figure 12.2f Illumination (footcandles) is the amount of light (lumens) falling on 1 square foot. Illumination can be measured with a photometer (light meter). In the SI system, illumination is measured in lux.

a table, an electric lamp, or a translucent window.

It is usually more important to consider the perceived brightness than the objective luminance. Lights will generally appear much brighter at night than during the day, but they will register the same luminance on a light meter at any time. Since we design lighting for people and not light meters, it is usually more important to focus on brightness than luminance.

SIDEBOX 12.2

Illuminance (inch-pound system)

$$\text{footcandles} = \frac{\text{lumens}}{\text{square feet of area}}$$

or

$$\text{fc} = \frac{\text{lm}}{\text{ft}^2}$$

Thus, the illumination of the table in Figure 12.2f is:

$$\text{illuminance} = \frac{80\,\text{lm}}{4\,\text{ft}^2} = 20\,\text{fc}$$

Illuminance (SI system)

$$\text{lux} = \frac{\text{lumens}}{\text{square meters}}$$

or

$$\text{lx} = \frac{\text{lm}}{\text{m}^2}$$

Thus, the illumination of the table in Figure 12.2f is:

$$\text{illuminance} = \frac{80\,\text{lm}}{4\,\text{ft}^2(.09\,\text{m}^2/\text{ft}^2)}$$

$$= 222\,\text{lux}$$

Note that this answer is approximately ten times larger than the 20 footcandles answer above, as is expected from the approximate conversion factor given in Table 12.2.

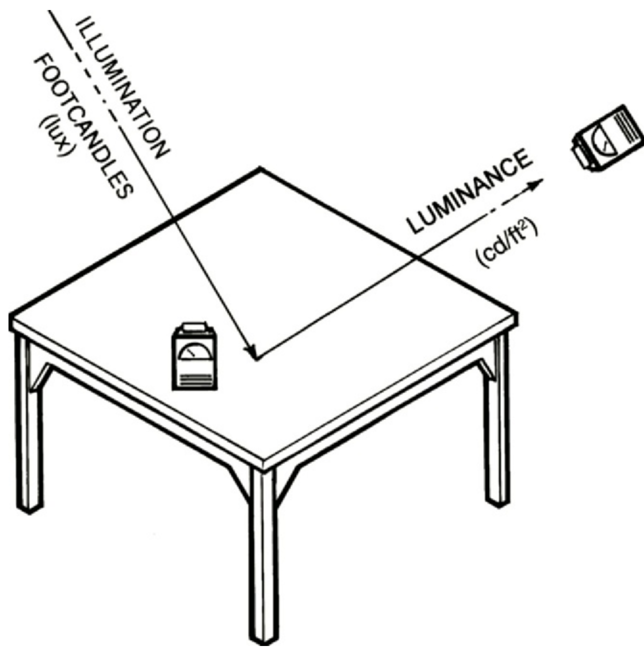


Figure 12.2g The luminance of the table is a function of the illumination, the color (reflectance), and the smoothness (specularity) of the table. Except for a perfectly flat (matte) surface, the luminance is also a function of the direction of the illumination and the direction of the luminance measurement.

In lighting, the switch to the International System (SI) from the inch-pound (I-P) system will be rather painless. Both systems use the unit of the lumen, and the unit of candlepower is equal to the SI candela. Lux is the SI unit for illumination and is approximately equal to one-tenth of a footcandle or

1 footcandle = approximately 10 lux (see Table 12.2).

12.3 REFLECTANCE/TRANSMITTANCE

Light falling on an object can be transmitted, absorbed, or reflected. The **reflectance factor (RF)** indicates how much of the light falling on a surface is reflected. To determine the RF of a surface, divide the reflected light by the incident light. Since the reflected light (brightness) is always less than the incident light (illumination), the RF is always less than 1, and since a little light is always reflected, the RF is never 0. A white surface has an RF of about 0.85, while a black surface has an RF of only 0.05. The RF, does not, however, predict how the light will be reflected, only how much. Very smooth polished surfaces, such as mirrors, produce specular reflections where the angle of incidence is equal to the angle of reflection. Very flat or matte surfaces scatter the light to produce diffuse reflections. Most materials reflect light in both a specular and a diffuse manner (Fig. 12.3a). See Table 13.3 for the reflectance of common materials.

Similarly, the **transmittance factor** describes the amount of light that is transmitted compared to the incident light. To determine the transmittance factor of a surface, divide the transmitted light by the incident light. A clear, **transparent** material

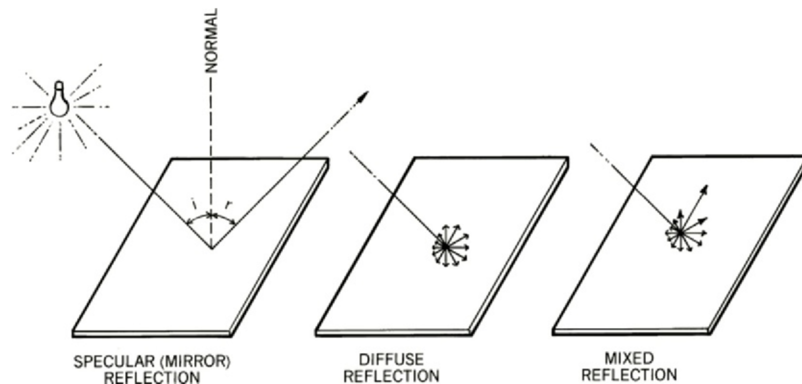


Figure 12.3a The characteristics of a surface determine not only how much but also in what way light is reflected. Most real materials tend to give mixed reflections.



Figure 12.3b Transparent materials do not distort the transmitted image, while translucent (frosted or milky) materials diffuse the light and destroy any image. Note the high brightness ratios created by the translucent glazing.

transmits the image of the light sources, while a diffusing **translucent** material like frosted glass scatters the light, thereby obscuring the image of the light sources (Fig. 12.3b). In general, diffusion does not affect the quantity of light transmitted (both clear and frosted glass transmit about 85 percent of the incident light).

There are three aspects to the reflection of light: the quantity (the RF), its manner (specular versus diffuse), and spectral selection (color). We have discussed the first two and will now discuss the third.

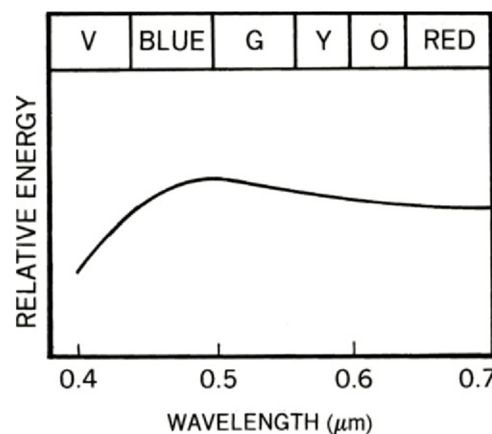


Figure 12.4a The spectral-energy distribution (SED) of average daylight at noon on a clear day in June. Notice the almost even distribution of the various colors (see also Colorplate 7).

12.4 COLOR

White light is a mixture of various wavelengths of visible light. Figure 12.4a illustrates the composition of daylight on a clear day in June at 12 noon. The horizontal axis describes the colors (wavelengths in millionths of a meter) and the vertical axis the amount of light (relative energy) at the various wavelengths. This kind of graph is the best way to describe the color composition of any light, and it is known as a **spectral-energy distribution (SED)** or **spectral-power distribution (SPD)** diagram. The mostly horizontal curve reflects the even mixture of the various colors that make up daylight. Only violet light is present in less quantity. North light, which is often considered the ideal white light for painters, is a less even mixture. It has more light in the blue end than the red end of the spectrum, as can be seen in the SED diagram of north light (Fig. 12.4b). Also compare Colorplates 7 and 8.

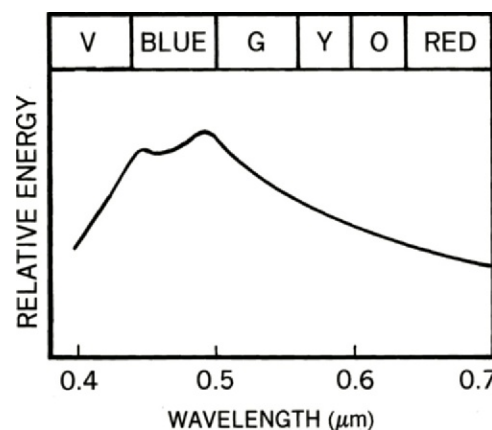


Figure 12.4b The spectral-energy distribution of daylight from a north-facing window. Note that there is more energy in the blue end than the red end of the spectrum (see also Colorplate 8).

Artists' studios used to face north not because north light was considered to have the best color balance but because, until recently, it was the most consistent source of white light. The main advantage of north glazing is the constancy of the light. Light from windows with other orientations varies greatly throughout the day and year. For example, late-afternoon daylight has much more energy in the red end of the spectrum and less in the blue end. Although all of the above varieties of daylight and many artificial light sources supply white light, there is a great difference in the composition of these sources.

The color of a surface is due not only to its spectrally selective reflectance characteristics but also to the spectral composition of the illumination. A completely saturated (pure) red paint that is illuminated by monochromatic (pure) red light will appear bright red because most of the light is reflected (Fig. 12.4c). However, if this same red paint is illuminated with monochromatic blue light, it will appear black because the color red absorbs all colors except red (Fig. 12.4d). Unless the red paint is illuminated with light that contains red, it will not appear red.

In the real world, where the colors are not completely saturated (pure), the situation is more complicated. An ordinary red reflects not only most of the red light but also small amounts of the other colors. This can create problems when the illumination does not have a good mixture of the various colors. A bright red car reflects plenty of red light when it is illuminated by daylight (Fig. 12.4e). However, when this same bright red car is parked at night under a clear mercury streetlight, it will appear to be brown (Fig. 12.4f). Since clear mercury lamps emit mostly blue, green, and yellow light, there is little red light that the car can reflect. Although much of the light of the other colors is absorbed, enough blue and green is reflected to overwhelm the red light.

When an object's color is very important, as, for example, in the displaying of meat or tomatoes, the selection of the light source is critical. A full-spectrum white light

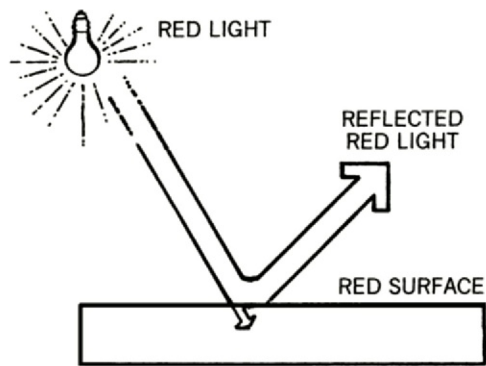


Figure 12.4c A red-colored surface reflects most red light and absorbs most of the light of the other colors.

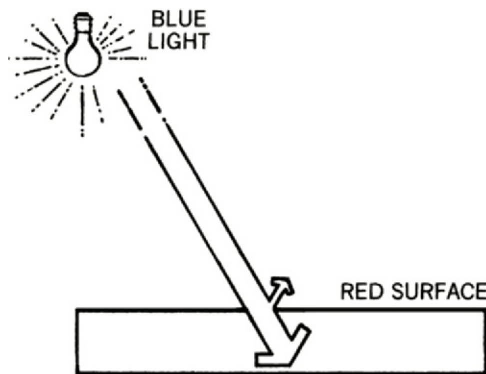


Figure 12.4d Under pure blue light, a pure red color will appear black since almost no light is reflected.

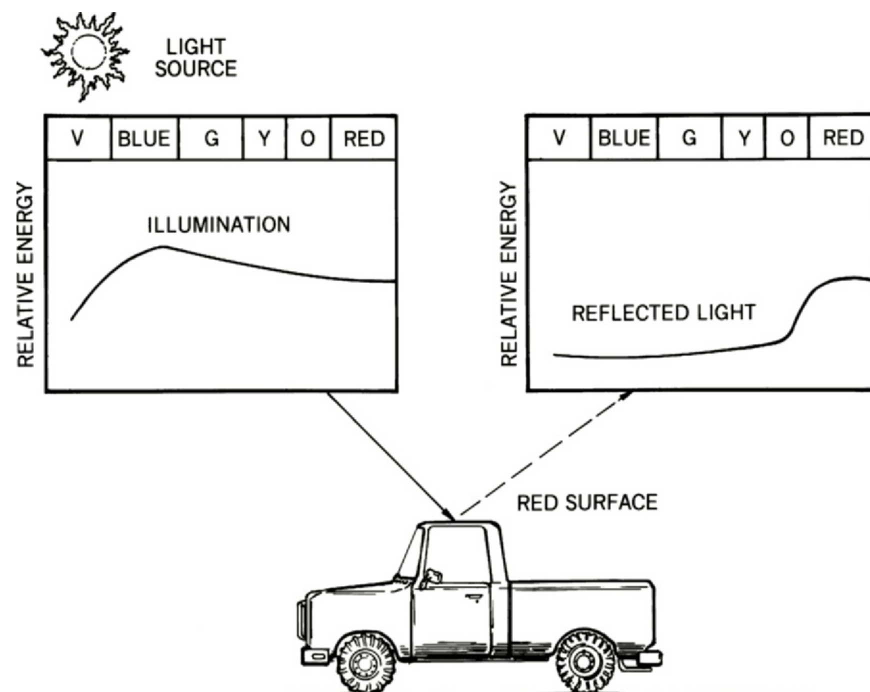


Figure 12.4e A red car will appear red if it is illuminated by a full-spectrum white light source, such as the sun.

source will accurately render the red colors of these items. To make them look even fresher and more appetizing, a light source rich in red could be used.

The transmission of light through colored glass or plastic is a selective process similar to reflection. A white light viewed through red glass will appear red because red light is mostly transmitted, and the light of the other colors is mostly absorbed (Fig. 12.4g).

Color Temperature

To completely describe the color content of a light source, the amount of light at each wavelength must be defined as in the SED diagrams of Colorplates 7 to 15. Because this method is quite cumbersome, the concept of **correlated color temperature (CCT)** is often used. Many materials, when heated, first glow red, then white, and finally blue. Thus, there is a relation between temperature and color. A CCT scale was developed that describes the color of a light source in kelvin (Fig. 12.4h and Colorplate 18).

CCT is mostly used to describe the warmness or coolness of a light source. Low CCT or warm light sources tend to render red colors well, while high CCT or cool light sources tend to render blue colors well. It must be noted, however, that this scale can give only a very crude description of the color-rendering ability of light sources. Another attempt to simplify the description of light sources was the development of the **color-rendering index (CRI)**, but it, too, has limitations and must be used with care. The CRI compares light sources to a standard source of white light. A perfect match would yield a CRI of 100, which is the value of daylight. A CRI of 90 is considered quite good, and a CRI of 70 is sometimes still acceptable (Colorplate 19).

Because of the simplicity of the CRI, it is tempting to rely on it too much. The CRI can be used only to

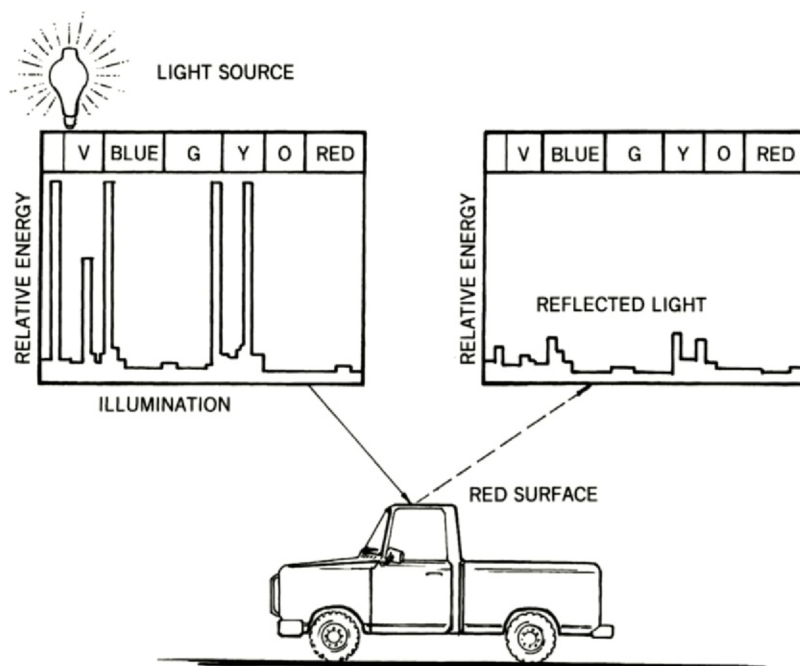


Figure 12.4f A red car will appear brown under light sources such as clear mercury lamps because these lamps emit only small amounts of red light. Thus, only a very small amount of red light is reflected from the car.

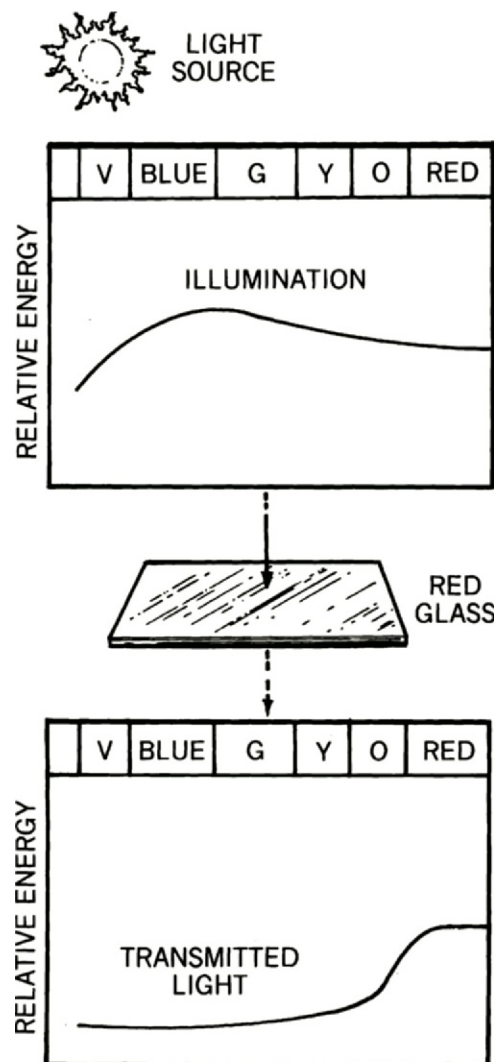


Figure 12.4g Red glass transmits most of the red light but only very little of the other colors.

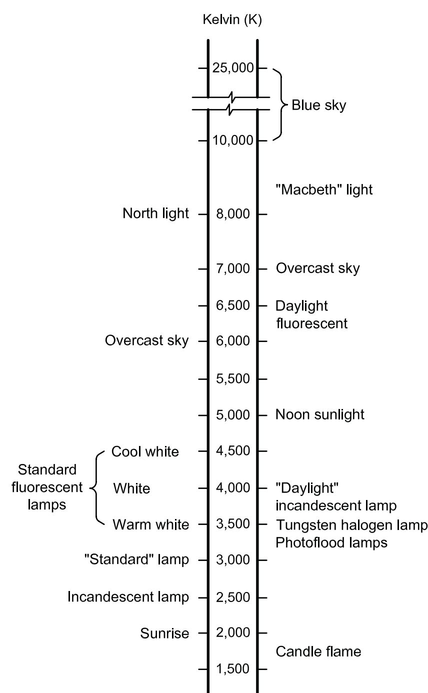


Figure 12.4h The color-temperature scale gives a rough indication of the color balance (spectral-energy distribution) of various sources of white light. (From *Mechanical and Electrical Equipment for Buildings*, by B. Stein et al., 10th ed., © John Wiley & Sons, Inc., 2006.)

compare light sources of the same color temperatures. Even then there is no guarantee that any specific color will appear natural.

Color selection or matching is best accomplished by actual tests. If colors are to be matched or selected, they must be examined with the type of light source by which they will be illuminated. Many designers have been shocked when they saw their carefully chosen colors under a different light source. The effect of light sources on color appearance is called **color rendition** and will be discussed in Chapter 14.

To see how two different light sources will render a specific color sample, a side-by-side comparison can be made with the setup shown in Figure 12.4i. A divider prevents light from either source from crossing over to the other color sample. Both samples must be seen at the same time because of a phenomenon of perception called color constancy, explained in Section 12.6.

Rules for Choosing White Light Sources

1. Full-spectrum white light is required for the accurate judgment of color.
2. People prefer white light sources between 3000°K (warm white) and 4100°K (cool white).
3. Warmer colors are preferred when illumination levels are low and to complement skin tones.

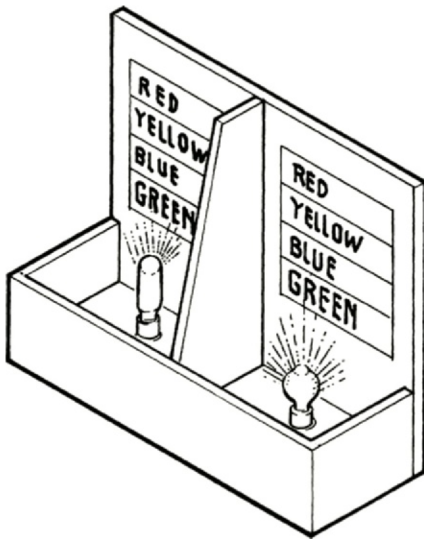


Figure 12.4i This device is used for comparing the color-rendering effect of two different light sources on the same color samples.

4. Cooler colors are preferred at high light levels and in hot climates.
5. Use 5000°K (cold white) light where very accurate color judgments must be made, as in studios.
6. Use a source with a CRI above 90 where color is important, and above 80 whenever possible. A CRI below 60 is unacceptable in most situations.

The color of an object is determined not only by its physical color but also by the composition of the light falling on it!

12.5 VISION

Vision is the ability to gain information through light entering the eyes. Rather than compare the eye to a photographic camera, which is the usual analogy, let's compare it to the video camera of a robot (Fig. 12.5a). The light rays that enter the video camera are transformed into electrical signals, and the robot's computer then processes these signals for their information content. The meaning of the signals is determined by both the hardware and software of the robot. Similarly, our eyes convert light into electrical signals that the brain then processes (Fig. 12.5b). Here also, the meaning of the visual information is a consequence of the hardware (eye and brain) and the software (associations, memory, and intelligence). The brain's interpretation of what the eyes see is called perception. Although a lighting design must ultimately be based on an understanding of perception, we must start by understanding vision.

Light enters the eye through an opening called the pupil and is focused on the light-sensitive lining at the back of the eye called the retina. The retina consists of cone cells that are sensitive to colors and rod cells that respond to motion and dim lighting conditions.

To accommodate the large range of brightness levels in our environment, the eye adapts by varying the size of the pupil with the muscle called the iris, as well as by a change in the sensitivity of the retina. The eye is able to see effectively in a range of brightness of 1000 to 1 and to partially see in a range of over 100,000,000 to 1. However, it takes about an hour for the eye to make a full adaptation; in the meantime, vision is not at its best.

Table 12.5 lists commonly experienced brightness levels and shows how these relate to vision. Although each item listed is ten times brighter than the previous item, we don't see it as ten times brighter. This illustrates the nonlinear sensitivity of the eyes and the consequence that it takes large increases in light for the eyes to notice a small increase in brightness.

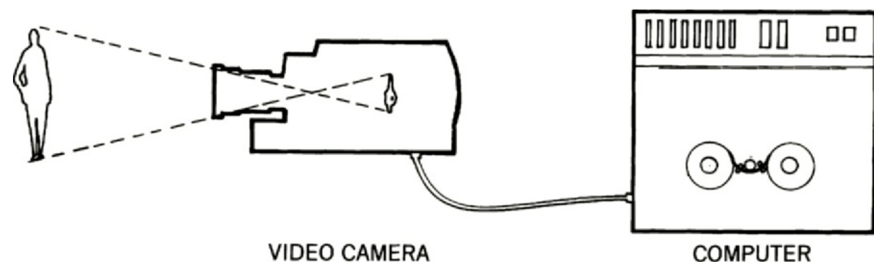


Figure 12.5a In robots that can "see," the computer brain interprets the electrical signals that come from the video camera.

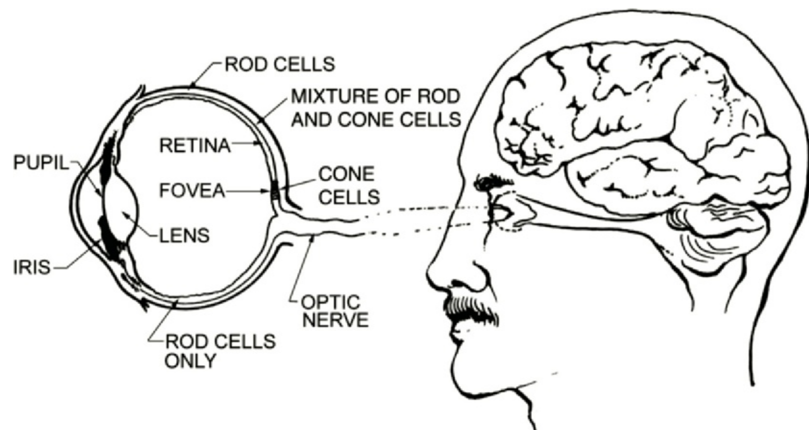


Figure 12.5b Light falling on the retina causes electrical signals to flow to the brain, which then interprets these signals for meaning.

Table 12.5 Commonly Experienced Brightness Levels

	Brightness		
	cd/ft^2	cd/m^2	
Sidewalk on a dark night	0.0003	0.00003	
Sidewalk in moonlight	0.003	0.0003	Poor vision
Sidewalk under a dim streetlight	0.03	0.003	
Book illuminated by a candle	0.3	0.03	
Wall in an office	3	0.3	Normal indoor brightness
Well-illuminated drafting table	30	3	
Sidewalk on a cloudy day	300	30	Normal outdoor brightness
Fresh snow on a sunny day	3000	300	
500 W incandescent lamp	30,000	3000	Blinding glare

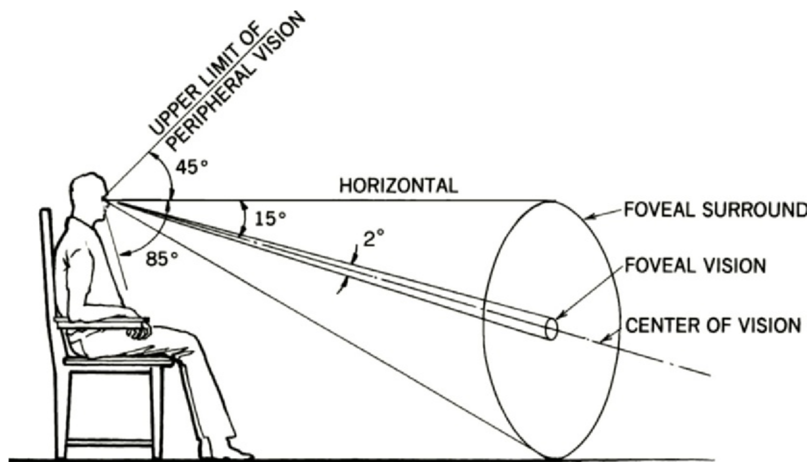


Figure 12.5c The center of vision and field of view are shown for a seated person with his head and eyes in the normal relaxed position. The foveal surround is a 30° cone within which brightness ratios must be carefully controlled.

Although rapid and extreme changes in brightness cause stress and fatigue, the eye is very well adapted to the gradual changes in brightness that are associated with daylighting. Because of the eye's adaptation, we perceive only small changes in light levels when clouds move across the sky. A gradual change in brightness is not a liability and might even be an asset because changes are more stimulating than static conditions.

A very small area of the retina surrounding the center of vision called the **fovea** consists mainly of cone cells. Here, the eye receives most of the information on detail and color (Fig. 12.5b). The foveal (sharp) vision occurs in a 2° cone around the center of vision, which moves as the eye scans. Focus, color, and awareness in the field of view decrease with distance from the central 2° cone of vision, because the density of cone cells decreases while that of rod cells increases (Fig. 12.5c). Rod cells respond to low light levels and movement but not to color or detail. Awareness is still quite high in the **foveal surround**, which is within a 30° cone around the center of vision. The nose, cheeks, and eyebrows are the limiting factors for peripheral vision, and the total field is, therefore, about 130° in the vertical direction and about 180° in the horizontal direction.

For a seated person whose head and eyes are at rest, the center of vision is about 15° below horizontal (Fig. 12.5c). The location and brightness of objects in the field of view will have a major impact on the quality of the lighting environment, as discussed in more detail later.

12.6 PERCEPTION

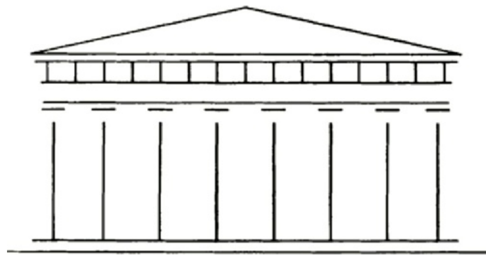
The ancient Greeks realized that we do not perceive the world as it actually is. They found that when they built their early temples with straight lines, right angles, and uniform spacing of columns, the results were perceived not as they built them (Fig. 12.6a) but distorted, as shown in Figure 12.6b. Consequently, the Greeks built later temples, like the Parthenon, in a very cleverly distorted manner (Fig. 12.6c) so that they would be perceived as correct (Fig. 12.6a).

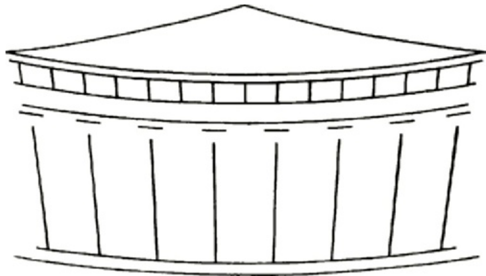
In the Parthenon, the columns are all inclined inward to prevent the illusion that they are falling outward. The columns have a slight bulge (entasis) to counteract the illusion of concavity that characterizes columns with straight sides. The column spacing and thickness vary because of the effect of high brightness ratios. Figure 12.6d illustrates how bright columns on a dark background look sturdier than dark columns on a bright background. This is important because the Parthenon's central columns are seen against the dark, shaded building wall, while the end columns are seen against the bright sky. Therefore, the ancient Greeks made the end columns thicker than the central columns.

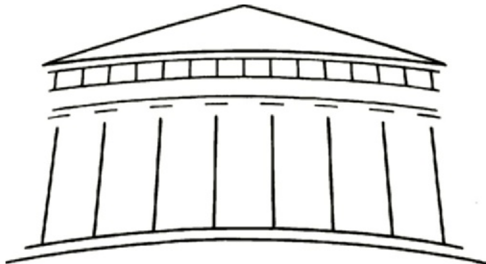
This example of temple design was not included to suggest that we should proportion our buildings as subtly as the ancient Greeks did, but to suggest how much perception can vary from what we might expect. To create a successful lighting system, the designer must understand human perception. Some of the more important aspects of perception are described below.

Relativity of Brightness

The absolute value of brightness, as measured by a **photometer (light**


Figure 12.6a Greek temples appear to be built with straight lines, square corners, and uniform spacing of the repeating elements.


Figure 12.6b When a temple was actually built as shown in Figure 12.6a, it was perceived as distorted in this manner (optical illusions).


Figure 12.6c The Parthenon was actually built in this distorted way so that it would be perceived as shown in Figure 12.6a.

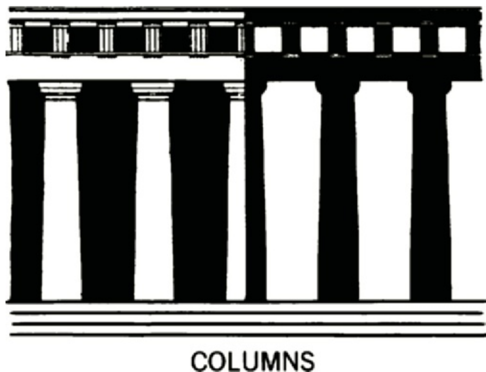


Figure 12.6d Some columns appear bright because of the shaded wall behind them. Corner columns seen against the bright sky seem dark in comparison. Because the darker corner columns appear smaller and weaker than the brighter columns, the Greeks made the end columns stouter than the central columns. (Figures 12.6a–12.6d are from Banister Fletcher's *A History of Architecture*, 19th ed., edited by John Musgrove, © Royal Institute of British Architects, 1987.)

meter) is called **luminance**. A human being, however, judges the brightness of an object relative to the brightness of the surroundings. Since the Renaissance, painters have used this principle to create the illusion of bright sunshine. The puddle of light on the table in the painting in Fig. 12.6e will appear as bright sunshine no matter how little light illuminates the painting. The painter was able to highlight objects by creating a dark setting rather than by high illumination levels. Figure 12.6f shows this same principle in an abstract diagram. The middle gray triangles are identical in every way, including their reflectance factor. Their luminance, as measured by a photometer, will be the same, but their perceived brightness will depend on the brightness of the surrounding area.

Because of the importance of this aspect of perception, one more example is in order. Car headlamps seem very bright at night but are just noticeable during the day. Although a meter would show the luminance to be the same, the brightness we perceive depends on the brightness of the headlamps relative to the overall lighting condition. This is partly due to the fact that at night, our wide-open pupils allow much of the light of the headlights to enter, while during the day, our small pupils shield us from the excess light of the headlights.

Brightness Constancy

To make sense of the visual environment, the brain has to make adjustments to what the eyes see. For example, in a room with windows on one end, the ceiling plane will appear of constant brightness, although a photometer would clearly show greater luminance near the windows. The brain knows that the reflectance factor is constant and that it is the illumination level that is varying. Consequently, the brain interprets the ceiling as having uniform brightness. This ability of the brain to ignore differences in luminance under certain conditions is called **brightness constancy**.

Color Constancy

It is common to have the experience of photographing a white building at sunset and then being surprised when the photograph comes back showing a pink building. The photograph tells the truth. Our perception fooled us into seeing a white building when we took the picture. Our brain filtered out much of the red light from the setting sun, something a camera can do also—but only when the lens is covered with a color filter or the white balance is adjusted in a digital camera. This ability of the brain to eliminate some of the differences in color due to differences



Figure 12.6e This Italian painter of the nineteenth century fully understood the concept of relativity of brightness. He could simulate bright sunshine by creating dark surroundings. The mind visualizes bright sunshine no matter how little light is falling on this painting. *The 26th of April 1859*, painted by Odoardo Borrani in 1861. (Courtesy of the Guiliano Matteucci-Studio d'Arte Matteucci, Rome, Italy.)

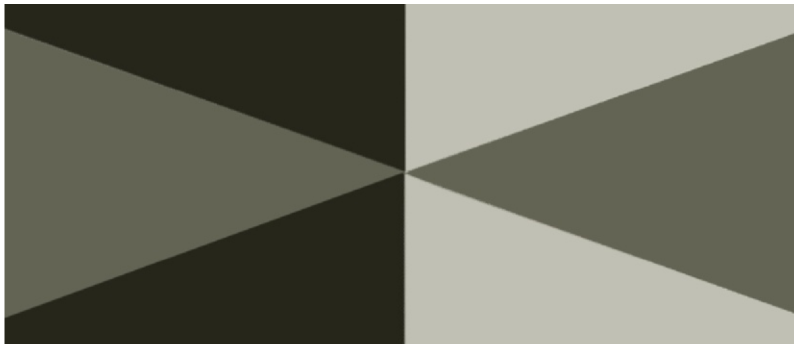


Figure 12.6f The two isosceles triangles are exactly the same, yet they appear to have different reflectance factors because of the phenomenon of the relativity of brightness. To see the triangles as equal, cover the dark areas around the left triangle with two pieces of white paper.

in illumination is called **color constancy**. This ability has very important survival implications because, without it, we would never recognize our own home if we returned at a different time of day.

Color constancy is not possible, however, if more than one type of light source is used simultaneously. Figure 12.6g illustrates what happens if an object is illuminated by north light from one side and an incandescent lamp from the other. One shadow will appear bluish and the other reddish because the brain cannot adjust to the color balance of each source simultaneously. A lighting design with different light sources must take this into account. Often, the best solution is not to mix light sources that are very different. The placement of clear window glazing adjacent to tinted glazing should also be avoided.

Although the brain makes some adjustment to perceived colors, cold north light will never look the same as warm, sunny sunlight. The adjustment due to color constancy is limited (Colorplate 16).

Other Color Perception Phenomena

The warm colors (red, orange, and yellow) appear to advance toward the eye, while the cool colors (blue, green, and dark gray) appear to recede. Thus, the choice of wall colors can make a space seem larger or smaller than it actually is.

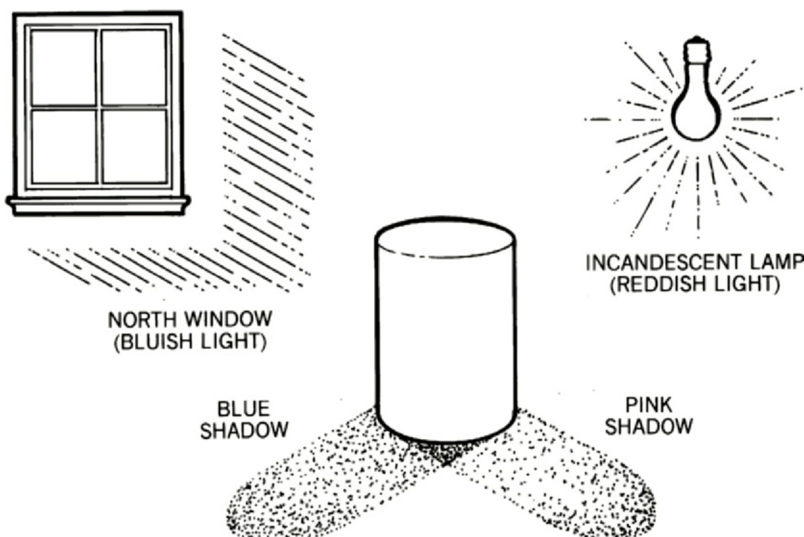


Figure 12.6g When more than one type of white light is used, color constancy cannot operate. One consequence is that shadows appear colored. However, if either source is eliminated, the remaining shadow will appear normal because color constancy can then be activated by the brain.

Prolonged concentration on any color will result in an afterimage of the complementary color. A surgeon staring at a bright red organ will see a green organ as an afterimage when she moves her eyes to look elsewhere. To minimize this upsetting phenomenon, hospitals now use green sheets and wall surfaces in their operating rooms. A green afterimage superimposed on a green sheet is much less noticeable than when it is superimposed on a white sheet.

Figure/Background Effect

The brain is always trying to sort out the visual signal from the visual noise. When this becomes difficult or impossible, the image becomes disturbing. Figure 12.6h illustrates a view interrupted by venetian blinds. In many cases, a properly designed overhang could achieve the same shading without any obstruction of the view.

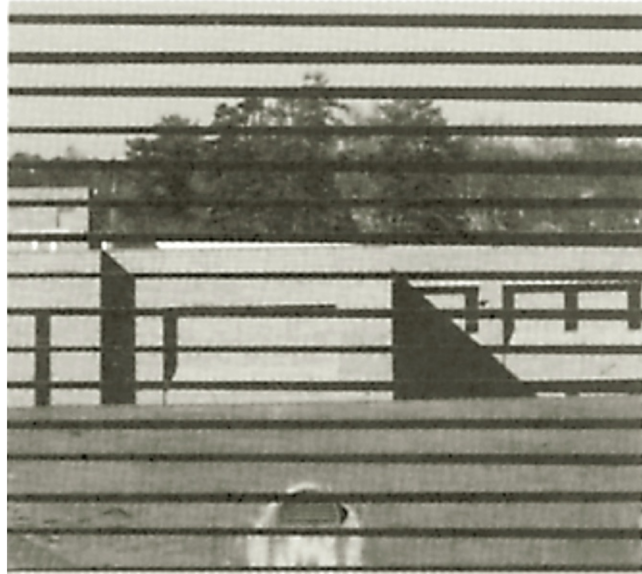


Figure 12.6h Venetian blinds are often disturbing because of the figure/background confusion.

Gestalt Theory

The purpose of seeing is to gather information. The brain is always looking for meaningful patterns. In Figure 12.6i, we see only a small circle and a long rectangle. But in Figure 12.6j, the first thing we see is the exclamation mark. In Figure 12.6k, we see a disturbing arrangement because it reminds us of something, but it is not quite right. The brain's search for greater meaning than the separate parts would suggest is called **Gestalt theory**. A particular lighting scheme will, therefore, be successful not only because all the parts are well designed but also because the whole composition is meaningful and not disturbing or distracting.

Other Perception Phenomena

Bright ceilings and upper walls make a room look larger and friendly, while dark ceilings and upper walls make a room seem smaller and less inviting.

Dramatic lighting is achieved by utilizing large brightness ratios in the field of view.

Romantic light, as from a candle on a dining table in a dark room, has several benefits. It creates an intimate space, it emits a very warm light whose reds complement skin complexion, and the nearly horizontal light tends to make facial wrinkles disappear.

Lighting must be designed for people's perception and not for light meters!

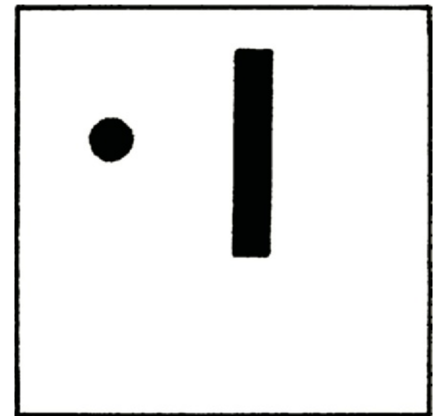


Figure 12.6i The brain perceives only a bar and a circle in this arrangement.

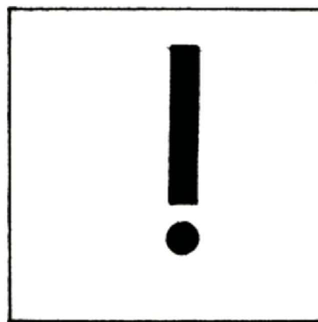


Figure 12.6j In this arrangement the brain perceives an exclamation mark rather than a bar and a circle. This perception of greater meaning is explained by Gestalt theory.

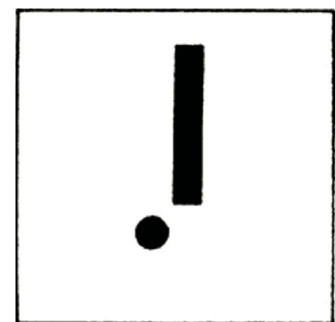


Figure 12.6k Since the brain is not sure if there is greater meaning, this pattern is disturbing.

12.7 PERFORMANCE OF A VISUAL TASK

Many factors affect the performance of a visual task (i.e., a task like reading, where visibility is important). Some of these factors are inherent in the task, some describe the lighting conditions, and the remainder reflect the condition of the observer. Most of the important factors can be easily understood by examining the common but critical seeing task of reading an interstate-highway sign (Fig. 12.7). Since the time of exposure is very limited, the signs are made large, bright, of high contrast, and of a consistent design. They are either well illuminated at night, or the lettering uses reflective paint. Sometimes, however, they are obscured by the glare of oncoming cars. The health and alertness of the driver are also factors. The basic factors that affect the performance of a visual task can be categorized as:



Figure 12.7 Since exposure time is limited, the other factors of visual performance are used to their maximum effect: size/proximity, brightness (night illumination), contrast, and familiarity (always white on green for exit signs.)

A. The task
  1. Size/proximity
  2. Exposure time
  3. Brightness
  4. Contrast
  5. Familiarity
B. The lighting condition
  1. Illumination level
  2. Brightness ratios
  3. Glare
C. The observer
  1. Condition of eyes
  2. Adaptation
  3. Fatigue level
  4. Health
  5. Effect of drugs and alcohol

Most of these factors will now be discussed in more detail.

12.8 CHARACTERISTICS OF THE VISUAL TASK

Size/Proximity

The most important characteristic of a visual task is the exposure angle, which is a function of the viewed object's size and proximity. The exposure angle will increase when the object is either enlarged or brought closer (Fig. 12.8a). In most cases, the brain then determines the cause by its familiarity with the real world and by means of binocular vision.

Whenever possible, the designer should increase the size of the task because a small increase in size is equivalent to a very large increase in illumination level. For example, a 25 percent increase in lettering size on a blackboard increases the visual performance as much as a change in illumination from 10 to 1000 footcandles (100 to 10,000 lux).

Exposure Time

Other factors of visual performance can offset a short exposure time, but, as with size, very high increases of illumination are required to offset small decreases in the exposure time. Thus, exposure time should not be cut short if at all possible.

Brightness

Figure 12.8b illustrates how an increase in task brightness, caused by increased illumination, at first results in significant improvements in visual performance, but additional increases yield smaller and smaller benefits. The "law of diminishing returns" is in effect because of the nonlinear relationship between brightness and visual performance. For example, in raising the illumination from 0 to 50 footcandles (0 to 500 lux), the brightness also increases proportionally, and the visual performance improves to about 29 percent of the maximum performance (lower curve), while another increase of 50 footcandles (500 lux) improves the visual performance only by another 4 percent. Since large increases in brightness are

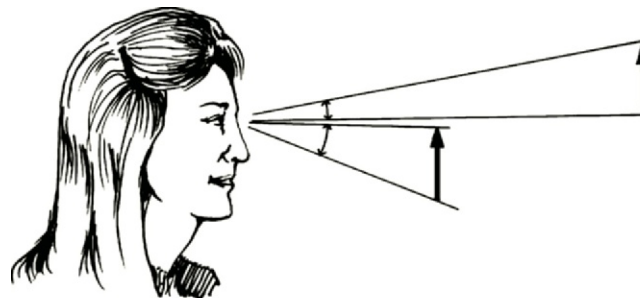


Figure 12.8a Size and proximity together determine the exposure angle.

made possible only by large increases in illumination, high brightness is a very expensive route to visual performance. The cost is in terms of both money and the environment.

Figure 12.8b also illustrates the impact of the exposure angle (size/proximity) on the performance of a visual task. Note that the performance at any light level of a large-size high-contrast task is about three times better than that of a small-size medium-contrast task.

The discussion so far has been about absolute brightness (luminance), but, as we saw earlier, we perceive brightness in relative terms. Therefore, it is often possible to increase performance by reducing the background brightness, thereby increasing the relative brightness of the task. The reduction of the background brightness increases the eye's sensitivity to light, making the task easier to see.

This concept is used to its fullest by museums exhibiting artifacts that light can damage. Wood, paper, cloth, and natural pigments all fade significantly when exposed to light. Such damage can be minimized by keeping the light level as low as possible. The museum shown in Figure 12.8c manages to highlight its fragile objects with fewer than 4 footcandles (40 lux) of illumination simply by having an even darker background illumination.

Although ultraviolet radiation causes the most damage to delicate objects, visible light also causes some fading. Short-wavelength radiation, such as that of violet and blue, is worse than the long-wavelength radiation of red.

Contrast

The difference in brightness between a detail and its immediate background is called **contrast**. Most critical visual tasks will benefit when the contrast between the task and its immediate surroundings is maximized. Writing, for example, is most easily seen when the contrast between ink and paper is at a maximum. When contrast decreases, the

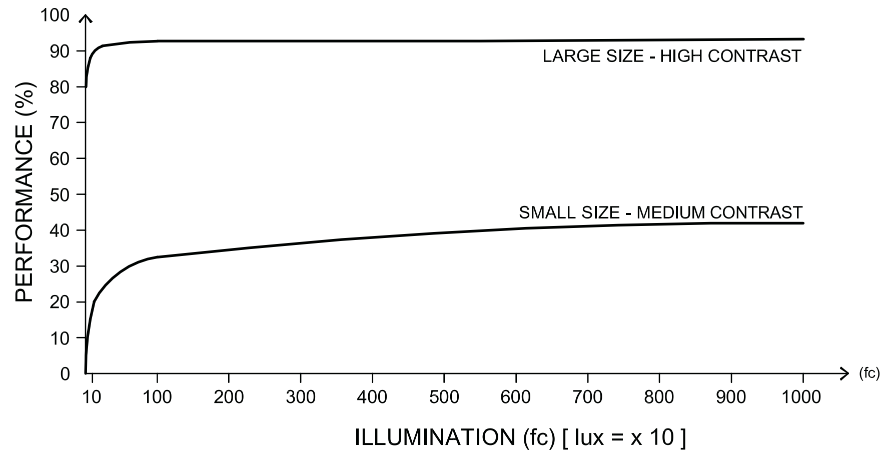


Figure 12.8b At first, visual performance improves rapidly with increase in illumination (brightness), but soon the law of diminishing returns governs. Above about 100 footcandles (1000 lux) there is little benefit with even large increases of illumination. For tasks of large size and high contrast, even 10 footcandles (100 lux) are enough. This graph also shows that no amount of light can make the performance of tasks of small size and medium contrast be the same as the performance of tasks of large size and high contrast. Thus, whenever possible, both the task and contrast should be adjusted. (After Boyce et al., 2000.)



Figure 12.8c Fragile artifacts from ancient Egypt are brightly illuminated by only 4 footcandles [40 lux] of illumination, yet they are easily seen because of the very dark background. The designer used the phenomenon of perception called relativity of brightness. (Courtesy of Memphis State Photo Services, Memphis State University, TN.)

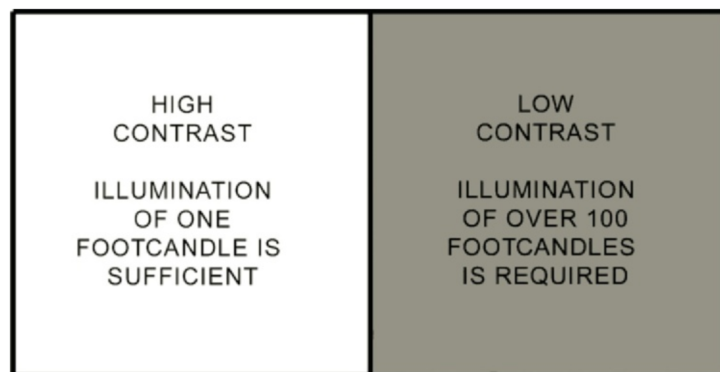


Figure 12.8d Contrast is an extremely important factor for the performance of many visual tasks. High levels of illumination are required to compensate for poor contrast.

other factors of visual performance can be adjusted to compensate. Again, however, very large increases of illumination are required to offset poor contrast (Fig. 12.8d).

It is important to note that the concept of contrast refers to detailed visual tasks (foveal vision), such as the print on a piece of paper. It does not refer to the brightness relationship of the paper to the desk or the desk to surrounding area. The brightness differences in these peripheral areas will have different effects on vision and will be discussed later.

12.9 ILLUMINATION LEVEL

Since brightness is directly proportional to illumination, the previous discussion on brightness is directly relevant to illumination. The graph in Figure 12.8b describes either the relationship between visual performance and illumination or brightness. As the light level increases to about 50 footcandles (500 lux), there is a significant improvement in visual performance. Above 100 footcandles (1000 lux), however, the law of diminishing returns begins to govern, and large increases in illumination result in only minor improvements in visual performance. The main reason for this is that the pupil gets smaller as the illumination increases. Thus, the amount of light reaching the retina increases only slightly.

It is, therefore, usually appropriate to keep the general area illumination below 30 footcandles (300 lux) and to supply higher light levels only if specific tasks require it. The additional light should be localized to the tasks that require it. This nonuniform approach to lighting is called **task lighting**.

The Illuminating Engineering Society of North America (IESNA) publishes recommended illumination levels for various activities. These recommendations are based on such factors as task activity, required speed, required accuracy, room-surface reflection factors (dark finishes require more light), and occupant age. For example, people in their twenties have a visual performance that is four times better than that of people in their fifties and eight times better than that of people in their sixties. Higher illumination levels can help offset the handicap of older eyes.

At the schematic design stage, however, only a very rough approximation of illumination levels is required for determining lighting strategies and for model studies. Table 12.9 gives guidelines for illumination levels appropriate for various activities. Unless otherwise specified, illumination levels are always given for horizontal work surfaces, and most tasks are performed on tables or desks that are about 2.5 ft (75 cm) high.

The ASHRAE Standard 90-75, which has been widely accepted as an energy code, makes the following recommendations about lighting:

1. Task lighting should be consistent with the IESNA recommendations.
2. General area lighting should be one-third of task lighting.
3. Noncritical circulation lighting should be one-third of general area lighting.

For example, in an office where the task lighting might be 75 footcandles (750 lux), the general area lighting would be 25 footcandles (250 lux), and the corridor lighting would be 8 footcandles (80 lux).

There is nothing absolute about these recommended light levels, as can be seen by the dramatic decrease in recommended light levels in the United States in the last thirty years (Fig. 12.9). Also, consider the very large discrepancy in what is recommended in various industrialized countries. Much more important than quantity is the quality of the light. The following discussion will explain the critical aspects of **quality light**.

To further demonstrate that the quantity of light is not the primary goal in lighting design, it is worthwhile to discuss the **Hawthorne effect**. A series of studies around 1930 on the effect of light levels on

Table 12.9 Guidelines for Illumination Levels*

Approximate Type of Activity	Examples	fc	lux
1. General lighting throughout space			
a. Public spaces with dark surroundings	Corridors at night	3	30
b. Simple orientation for short, temporary visits	Residential (nonwork), restaurants	8	80
c. Working spaces where visual tasks are only occasionally performed	Corridors, lobbies, churches	15	150
2. Illumination on task			
a. Performance of visual tasks of high contrast or large size	Residential (kitchens and other work areas), hotels	30	300
b. Performance of visual tasks of medium contrast or small size	Offices, classrooms, banks	75	750
c. Performance of visual tasks of low contrast and very small size over a prolonged period	Design studios, critical work areas	150	1500

*Based on IESNA recommendations. Precise values are not appropriate because of the large tolerance of human vision. However, the following adjustments should be made:
1. Increase illumination about 50 percent for any of the following reasons: room surfaces are dark, many people are over age fifty, or the tasks are difficult and/or critical.
2. Decrease the illumination about 50 percent for any of the following reasons: the quality of the lighting is very high, the room surfaces are very light, most people are below age forty, or the tasks are neither difficult nor critical.

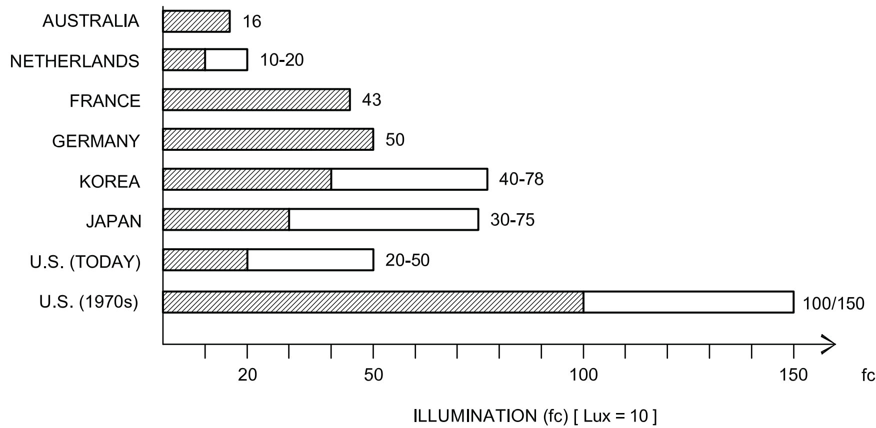


Figure 12.9 A comparison of recommended lighting levels for general office work in horizontal footcandles. Note that some countries recommend ranges instead of a specific value. Also note how the recommended illumination levels have dropped in the United States since the 1970s. (After Mills and Borg. "Rethinking Light Levels." *IAEEL Newsletter* 7 (20), 4–7 (1998).)

productivity showed that both an increase and a decrease in illumination levels could cause an increase in productivity. This apparently absurd result indicated that other factors were much more important than illumination levels in affecting productivity in a visual task. Further research showed that motivation and attitudes toward the job had a far greater impact. A good way for a lighting designer to incorporate the Hawthorne effect would be to give each worker control over his or her own lighting. Both physiological and psychological needs are addressed by a task light that has both flexible arms and a brightness adjustment.

The quality of light is much more important than the quantity, above a certain minimum!

12.10 BRIGHTNESS RATIOS

Although the eye can adapt to large variations in brightness, it cannot adapt to two very different brightness levels simultaneously. This problem can be easily visualized by looking at photographs of a building entrance. In Figure 12.10a, the camera was set to correctly expose the exterior; consequently, the view of the interior is too dark to see. On the other hand, in Figure 12.10b, we see the same entrance from the indoor side and the camera was set to correctly expose the interior. The result is that the out doors is too bright to see. There is no way that the camera itself can overcome the problem of the excessive **brightness ratio** between indoors and outdoors. Professional photographers usually wait until



Figure 12.10a In this photograph, the camera was adjusted to correctly expose the high brightness of the exterior. We cannot see indoors because the brightness there is too low compared to the outdoors. This is a problem of excessive brightness ratios.



Figure 12.10b In this photograph, the camera was adjusted to correctly expose the interior. Consequently, we cannot clearly see the outdoor view because it is too bright compared to the interior. This is a problem of excessive brightness ratios.

Table 12.10 Maximum Recommended Brightness Ratios for Indoor Lighting*

Ratio	Areas	Example
3:1	Task to immediate surroundings	Book to desktop
5:1	Task to general surroundings	Book to nearby partitions
10:1	Task to remote surroundings	Book to remote wall
20:1	Light source to large adjacent area	Window to adjacent wall

*For high visual performance in a normal work area, these brightness ratios should not be greatly exceeded. However, uniform brightness is not desirable either. The task should be slightly brighter than the immediate surroundings to avoid distraction. This table does not apply in situations in which dramatic highlighting, mood lighting, or aesthetic concerns should be dominant.



Figure 12.10c Although this room has more than enough illumination on the horizontal work surface, it appears dark because of the low brightness of the vertical surfaces. (Photograph by James Benya.)

early evening, when the indoor and outdoor brightnesses are nearly equal. Another option is to greatly increase the indoor illumination.

Although the eye can minimize this problem by concentrating on one brightness area at a time, all brightness areas in the field of view have some impact. The result of too high a brightness ratio is visual stress. If the eye keeps switching back and forth between areas of very different brightness, the additional stress of constant readaptation will also be present.

Lighting designers can avoid these sources of visual stress by controlling the brightness ratios in the field of view. They can accomplish this by adjusting reflectance factors as well as the illumination of surfaces, since brightness is a function of both. The eye is most sensitive to brightness ratios near the center of vision and least sensitive at the edge of peripheral vision. Consequently, the acceptable brightness ratios depend on the part of the field of view that is affected. For good visual performance such as that required in an office, the brightness ratios should be kept within the limits shown in Table 12.10.

The first step in designing brightness ratios is to choose the reflectance factors of all large surfaces. In work areas such as offices, the following minimum reflectances are recommended: ceiling, 80 percent; vertical surfaces such as walls, 60 percent; and floors, 40 percent (see Figure 12.11k). Dark walls, especially, should be avoided. A small sample of dark wood paneling can be quite attractive, but a whole wall of it is likely to be oppressive. Additional control of brightness ratios is then achieved by selective illumination. Although the illumination on the work surface is more than adequate, the walls in Figure 12.10c are not bright enough. Figure 12.10d shows the same room with additional illumination on the vertical surfaces.



Figure 12.10d Additional illumination on the vertical surfaces makes this room appear less dark. (Photograph by James Benya.)

12.11 GLARE

Glare is visual noise that interferes with visual performance. Two main types of glare exist, direct and reflected, and each can have very detrimental effects on the ability to see.

Direct Glare

Direct glare is caused by a light source in the field of the view that is sufficiently bright to cause annoyance, discomfort, or loss in visual performance. It is called **discomfort glare** when it produces physical discomfort and **disability glare** when it reduces visual performance and visibility. The severity of the glare that a light source causes is due largely to its relative brightness. High-beam headlights can cause blinding glare at night, but hardly any glare during the day. Similarly, a bare lamp against a black ceiling causes much more glare than the same lamp seen against a white ceiling. This is one of several reasons why ceilings should usually be white.

Direct glare is also a consequence of geometry. The closer an offending light source is to the center of vision, the worse the glare. Of all the light sources in Figure 12.11a, the window and lamp C are closest to the center of vision and, therefore, serious sources of glare, while lamp A is not a source of glare at all because it is completely outside the field of view for the observer at the location shown. Geometry also affects the exposure angle, which is a function of both size and proximity. Large exposure angles from large or close light sources also result in more glare than small exposure angles from small or more distant light sources. Thus, glare changes greatly from point to point in a room.

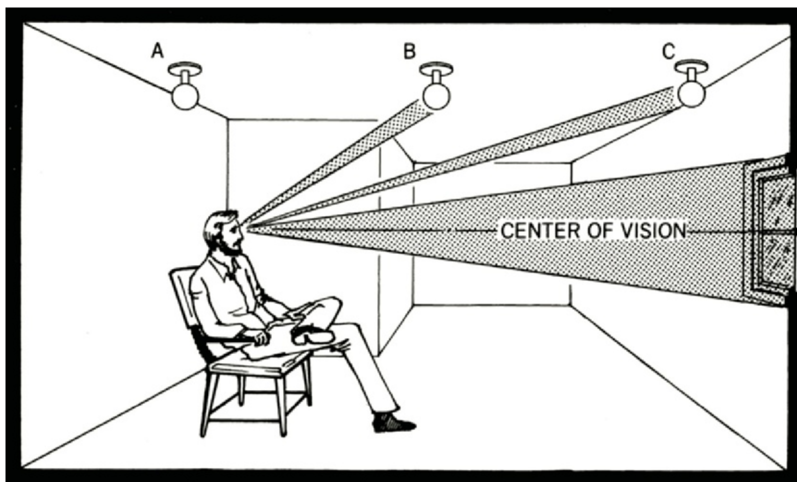


Figure 12.11a Light sources near the center of vision cause more direct glare than those at the edge of the field of view. For the person seated as shown, light A causes no glare at all.

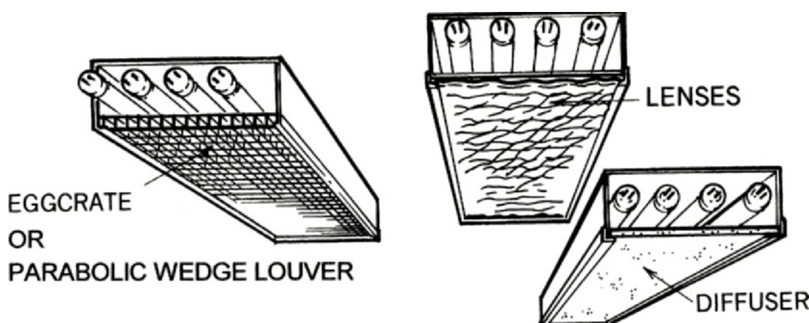


Figure 12.11b Eggcrates, parabolic louvers, baffles, and lenses limit direct glare by controlling the direction of the light emitted from lighting fixtures. Diffusers limit glare by reducing the brightness of the light source.

Since ceiling-mounted lighting fixtures are a likely source of direct glare, much research has been conducted to quantify and reduce the glare these fixtures cause. **Eggcrates**, parabolic louvers, lenses, and diffusers are commonly used to minimize glare from lighting fixtures (Fig. 12.11b). These optical controllers eliminate or reduce the light emitted in the direct-glare zone (Fig. 12.11c). Note how the direct-glare zone of the light source (45° below the horizontal) corresponds to the direct-glare zone of the viewer (45° above the horizontal). Because indirect lighting uses the ceiling as a large-area, low-brightness reflector, it creates almost no glare at all. The impact of lighting-fixture design and the benefits of indirect lighting are explained in more detail in Chapter 14.

Since lighting fixtures vary greatly in the amount of direct glare that they produce, the concept of **visual comfort probability (VCP)** was developed. The VCP factor predicts the percentage of people who will find a specific lighting system acceptable with regard to direct glare. Indirect lighting fixtures, because of their low brightness, come close to the maximum of 100 percent.

We must not forget that lighting design is a problem not just in physics, but also in human perception. The same light source that creates glare in an office might create sparkle in a nightclub. What is noise in one situation can be an information signal in another.

Indirect Glare

Reflections of light sources on glossy tabletops or polished floors cause a problem similar to direct glare.

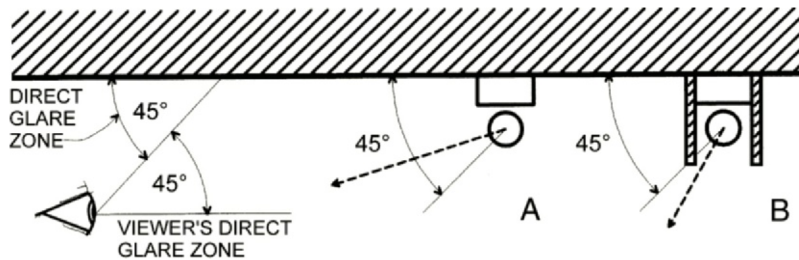


Figure 12.11c Lighting fixture A causes glare because light is emitted within the direct-glare zone, while the shielded fixture B does not cause direct glare. Note how the fixture's and viewer's direct-glare zones correspond.



Figure 12.11d Veiling reflections impair the visual performance of a task by reducing contrast.

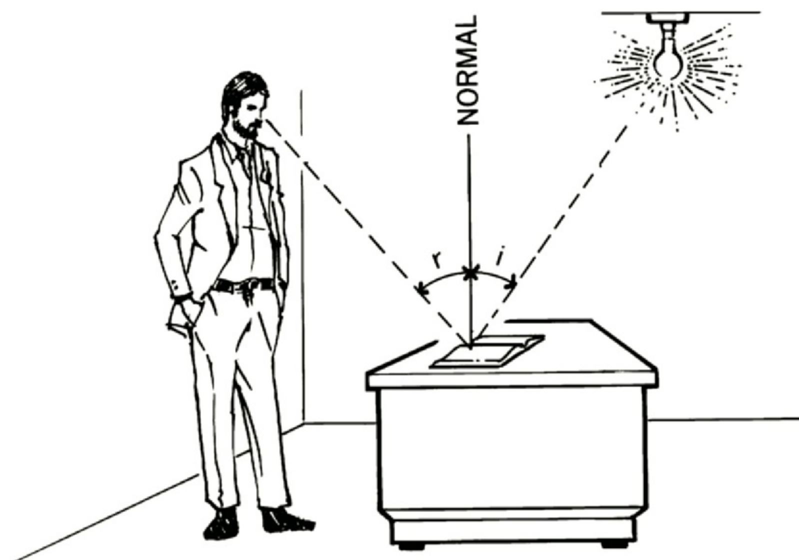


Figure 12.11e Veiling reflections are at a maximum when the angle of incidence (*i*) equals the angle of reflection (*r*).

Note the reflected glare from the polished floor and glossy metal lockers in the photo of Figure 12.10b. **Indirect glare** is often best avoided by specifying flat or matte finishes. However, when the task has a glossy surface, the lighting system has to be designed to avoid producing this reflected glare. If shiny surfaces cannot be avoided, then indirect glare can be minimized by using a diffused light source or by working with geometry, as will be explained in the following section on veiling reflections.

Veiling Reflections

The reflections of bright light sources on such tasks as glossy printed pages are known as **veiling reflections** because they reduce the contrast necessary for good visual performance (Fig. 12.11d). The sheen of the reflected light hides or veils the image of a picture or text. Veiling reflections are specular, or mirror-like, reflections that are most severe on very smooth materials but also exist to a lesser degree on semigloss surfaces. Pencil marks and some inks quickly disappear under veiling reflections because of their glossy finish. Their sheen will be just as bright as the white background and all contrast is lost.

Veiling reflections are at a maximum when the angle of incidence, established by the light source, equals the angle of reflection, established by the location of the eye (Fig. 12.11e). Most people seated at a desk will do their reading and writing in a zone ranging from 25° to 40° measured from the vertical. Any glossy material in this zone will reflect light from a related zone in the ceiling (Fig. 12.11f). Any light source in this **offending zone** of the ceiling will be a cause of veiling reflections. In an existing lighting design, this offending zone is easy to spot simply by substituting a mirror for the visual task (Fig. 12.11g). Similarly, an imagined mirror can help visualize the offending zone in a proposed design. Thus, it is easy to understand how the offending

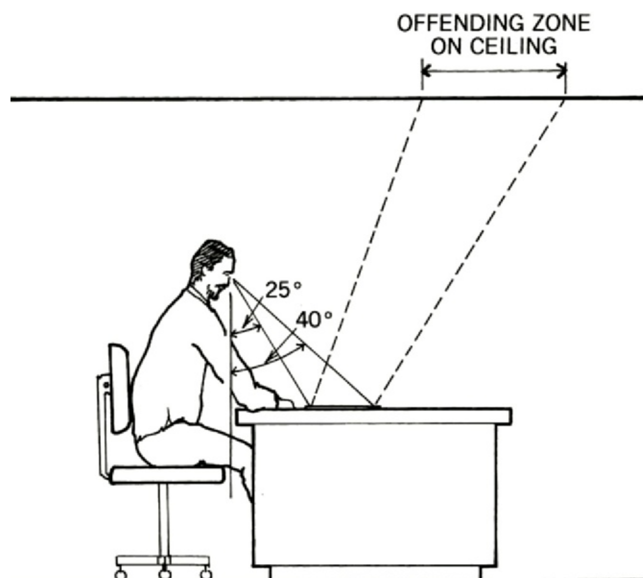


Figure 12.11f Any light source in the offending zone can create severe veiling reflections for a person working at a table or desk. The offending zone will shift if the task or table is tilted (e.g., a drafting table).

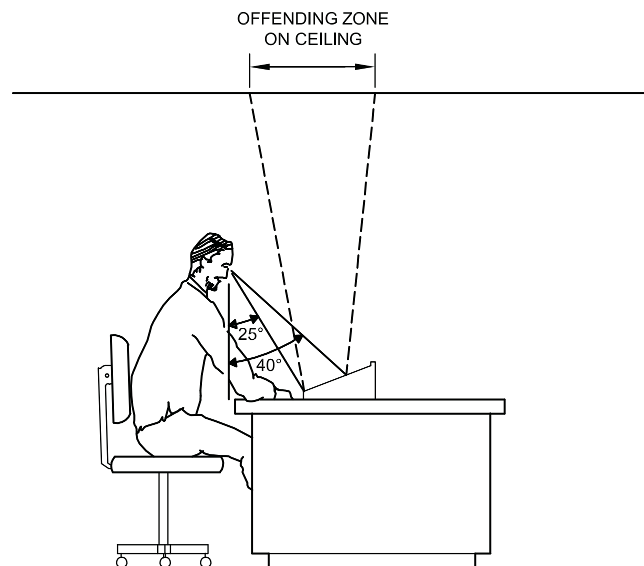


Figure 12.11h When the task is tilted, the offending zone shifts.

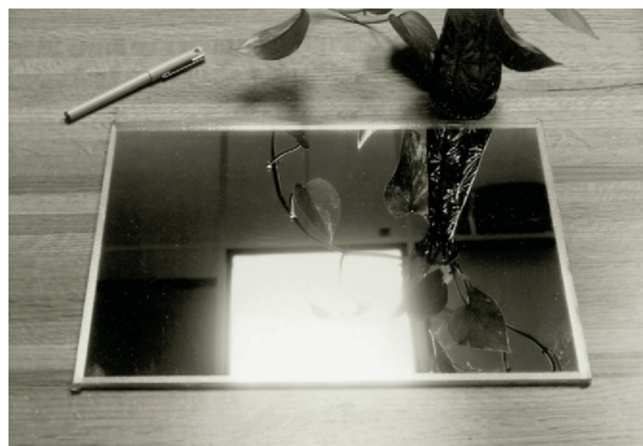


Figure 12.11g By replacing the task with a mirror, any bright light source in the offending zone will be visible. Hold the mirror vertically if the task is in a vertical plane (e.g., a painting or computer monitor).

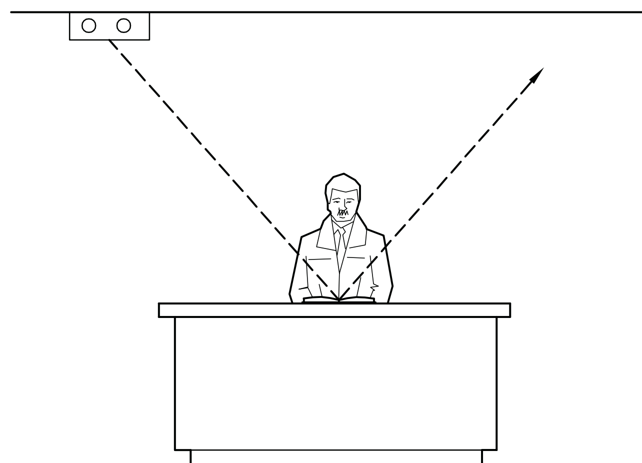


Figure 12.11i To prevent both veiling reflections from front lighting and the casting of shadows from back lighting, the light should come from the sides.

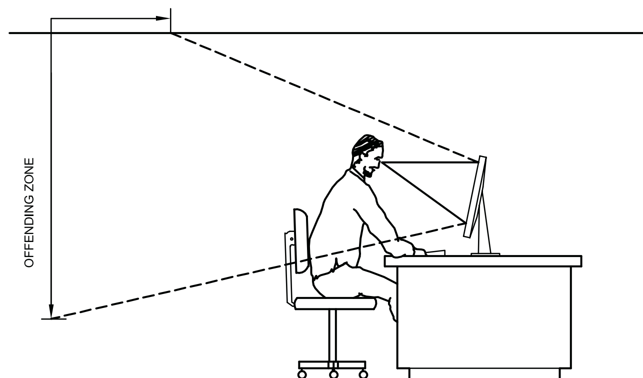


Figure 12.11j The rear wall and ceiling become the offending zone when the task is vertical or nearly vertical.

zone shifts if the task is tilted (Fig. 12.11h). It is also easy to understand that light sources behind or to the right or left of the viewer cannot be seen in a mirror on the table and, thus, are not in the offending zone (Fig. 12.11i). However, if the task is nearly vertical, as with a computer monitor, the offending zone will be behind the viewer (Fig. 12.11j).

Veiling reflections are the most serious problem that the lighting designer faces. It is a problem not

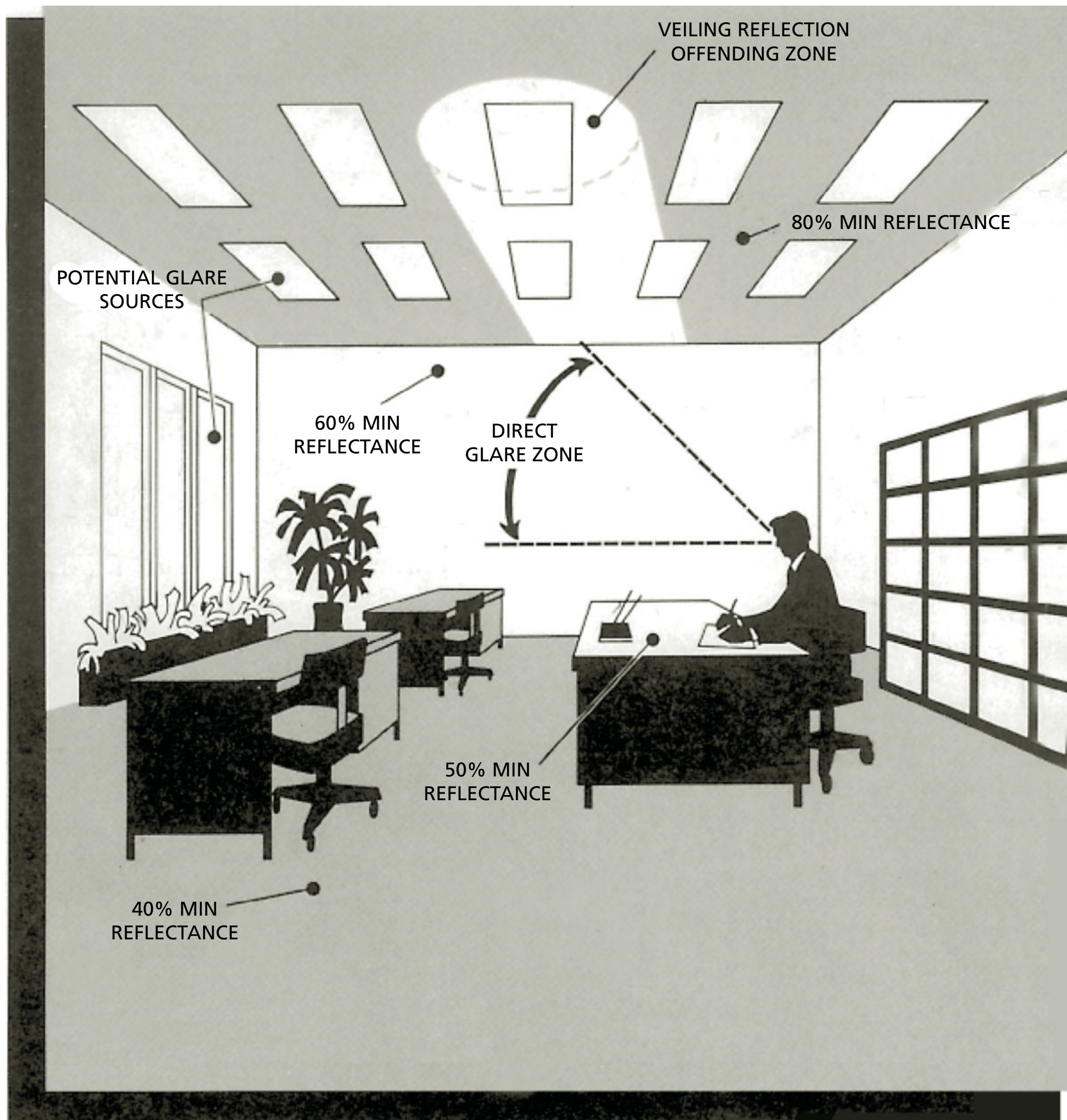


Figure 12.11k Sources of direct glare and veiling reflections are shown. Recommended reflectance factors are also shown. (Courtesy of General Electric Lighting.)

only for people working behind a desk but also for others, such as workers handling smooth parts, people viewing artwork through glass, etc. The problem is getting even more serious with the extensive use of computers. The avoidance of glare and veiling reflections is the top priority in most lighting designs. Figure 12.11k illustrates the sources of veiling reflections and direct glare. The diagram also shows common reflectances that will produce acceptable brightness ratios in the field of view. Much of the remainder of this chapter and the following chapters on daylighting and electric lighting discuss how to control glare and veiling reflections.

The quality of a lighting environment is largely the function of the glare, veiling reflections, and brightness ratios.

12.12 EQUIVALENT SPHERICAL ILLUMINATION

Veiling reflections are so detrimental to visual performance that increased lighting at the wrong angle can actually reduce our ability to see. Above a certain minimum, the quality of the light is more important than the quantity. Ordinary raw footcandles of illumination, as measured by a photometer, can be meaningless if

the geometry of the lighting is not included. To correct this serious deficiency, the concept of **equivalent spherical illumination (ESI)** was developed.

Sphere illumination is a standard reference condition with which the actual illumination can be compared. In sphere illumination, the task receives light from a uniformly illuminated hemisphere (Fig. 12.12a). Since the task is illuminated from all directions, only a small amount of the total light will cause veiling reflections. Although spherical illumination is of high quality, it could be improved by eliminating that small portion of light causing veiling reflections. Sphere illumination is a valuable concept not because it represents the best possible lighting, but because it is a very good reproducible standard with which any actual lighting system can be compared.

An actual lighting system that supplied an illumination of 250 footcandles (2500 lux) might be no better than an equivalent spherical illumination of 50 ESI footcandles (500 lux). This means that the quality of the actual system is so poor that 200 out 250 footcandles (2000 out of 2500 lux) are useless. Therefore, the ESI footcandles can tell us how effective the raw footcandles are. ESI enables us to describe the quality as well as the quantity of the illumination.

In the lighting layout plan shown in Fig. 12.12b, we can see that the quality of the lighting varies greatly with location and that raw footcandles are not a good indication of visual performance. Notice that if only raw footcandles were considered, location C would be the worst choice for the desk because it has the lowest illumination level. In fact, location C is by far the best, as the very high ESI footcandle level indicates. Locations A and B will both experience serious veiling reflections from the overhead lighting fixtures. This situation can be visualized via the mirror test (Fig. 12.11g). Imagine a mirror placed on each desk in place of the task. The person occupying desk A will see the most lighting fixture in the offending zone, while the person at desk C will see only the ceiling in its offending zone.

Since quality compensates for quantity, the lighting levels that the IESNA recommends can be reduced by 25 percent if veiling reflections are largely avoided. Recommended light levels are still given in raw footcandles because it is very difficult and expensive to measure ESI footcandles.

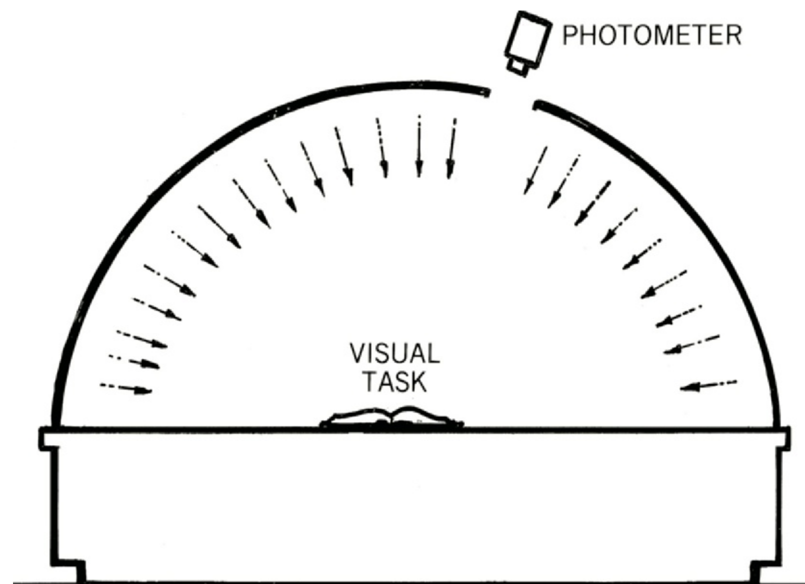
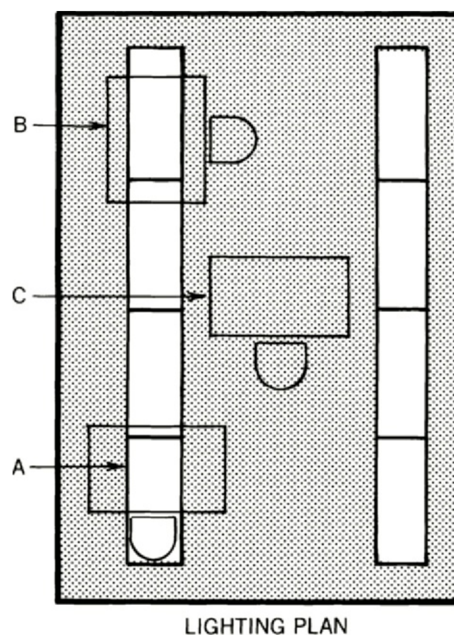


Figure 12.12a A section through the test chamber for measuring equivalent spherical illumination (ESI) is shown.



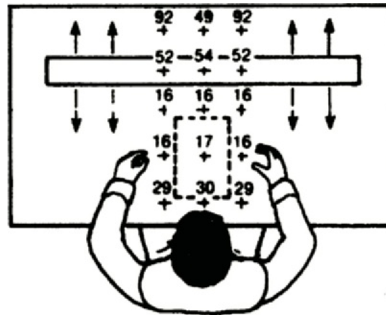
	DESK		
	A	B	C
RAW FOOTCANDLES	100	120	90
ESI FOOTCANDLES	17	30	90

Figure 12.12b This reflected ceiling plan also shows the location of the desks. A comparison of raw and ESI footcandles for three different locations clearly shows that desk C has the best lighting. Although desk B has the highest illumination level, the veiling reflections neutralize most of the footcandles. Desk A has the worst lighting of all.

12.13 ACTIVITY NEEDS

The requirements for good visual performance mentioned so far apply to most visual tasks. However, additional requirements vary with the specific visual task.

1. *Reading and writing*. The avoidance of veiling reflections has the highest priority for the activities of reading and writing. Light should, therefore, come from the sides or from behind but never from in front of the observer. Notice in Figure 12.13a how much higher the ESI footcandles are on a desk when the light comes from the sides rather than from in front. The light should come from at least two sources to prevent workers from casting shadows on their own task.
2. *Drafting, drawing, and painting*. Because of the somewhat glossy finish of drafting films, pencil lines, ink, and paint, veiling reflections are a major problem. Shadows from drafting instruments also obscure the work. Very diffuse general lighting with task lighting from both sides is appropriate on both accounts.
3. *Observing sculpture*. Shades and shadows are necessary in understanding the three-dimensional form of an object. The appropriate lighting should, therefore, have a strong directional component (Fig. 12.13b). Unless there is some diffused light, however, the shadows will be so dark that many details will be obscured (Fig. 12.13c), but completely diffused lighting is not appropriate either, because it makes objects appear flat and some three-dimensional details will tend to disappear (Fig. 12.13d). Usually, the directional light should come from above and slightly to one side because that is the way the sun generally illuminates objects, and we are used to that kind of modeling. Seeing familiar objects like the human face



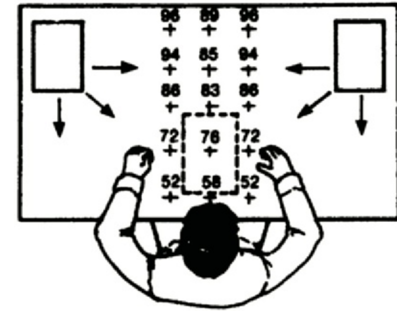


Figure 12.13a The ESI footcandles are quite low for the lighting fixture in front of the task because of the veiling reflections. With fixtures on both sides, there will be almost no veiling reflections, and consequently the ESI footcandles are much higher, although the total wattage is lower. Left: one 40 W lamp: right: two 14 W lamps. Two fixtures are used to prevent shadows from hands. (Courtesy of Cooper Lighting.)



Figure 12.13b The best modeling occurs with strong directional light along with some diffused light to soften the shades and shadows.

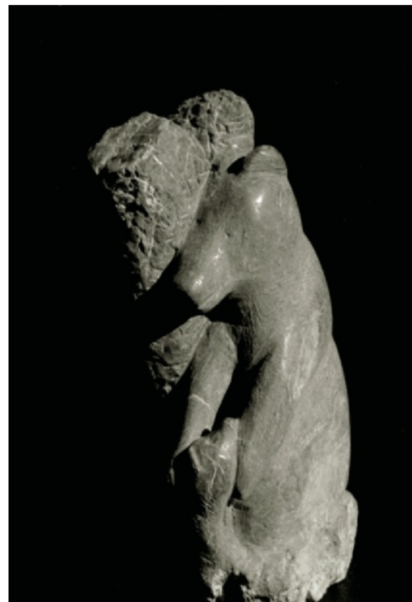


Figure 12.13c If all the light comes from one direction, strong shadows and shade will obscure much of the object.



Figure 12.13d Some parts of an object will appear flat under mostly diffused light.

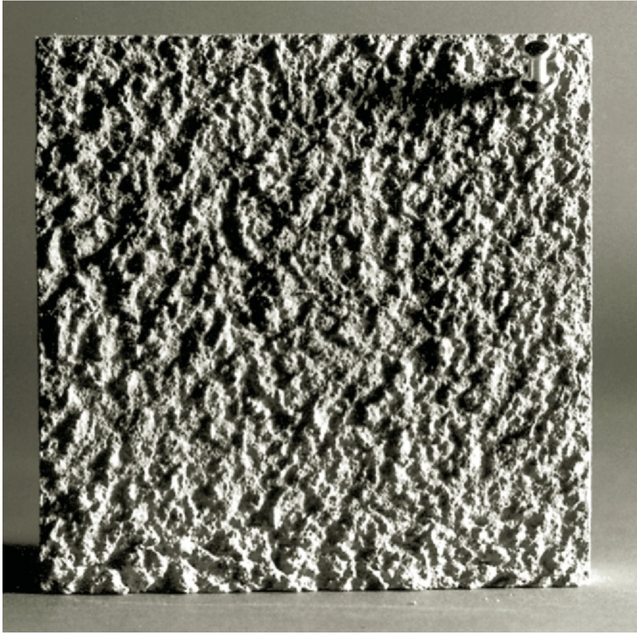


Figure 12.13e Texture is most visible under glancing light. Note the long shadow of the pushpin in the upper right corner.



Figure 12.13f The same texture seen under straight-on or diffused light. Note the lack of a shadow from the pushpin.

lit from below can be a very eerie experience.

4. *Seeing texture*. The appearance of texture depends on the pattern created by shades and shadows. A texture is, therefore, made most visible by glancing light that maximizes the shades and shadows (Fig. 12.13e). The same material seen under diffused or straight-on lighting will appear to have almost no texture (Fig. 12.13f). Glancing light can also be used to investigate surface imperfections; conversely, glancing light should be avoided if surface imperfections are to be hidden.
5. *Looking at paintings*. When one highlights paintings, glossy artwork, or art behind glass, the challenge is to prevent specular reflections of the light sources into the viewers' eyes. Many a fine print protected by glass has become invisible because of veiling reflections (Fig. 12.13g). The



Figure 12.13g It is impossible to appreciate this glass-covered work of art in a famous museum because of the reflected glare caused by a circular downlight (top center of picture) and because of the veiling reflections caused by bright surfaces behind the viewer.

accent light must be placed in front of the offending zone so that people of various heights and at different locations will not see the specular reflection of the light source (Fig. 12.13h). However, if the light is too close to the wall above the painting, the top of the picture frame will cast a shadow and the texture of the painting will be overemphasized. In most cases, a 60° aiming angle will be a good compromise (Fig. 12.13i). When the artwork is covered with glass, special antireflectivity glass, which makes the lighting much less critical, can be specified (Fig. 12.13j).

6. *Windows*. Because glass transmits about 90 percent and reflects about 10 percent of the light, we always see both the transmitted and reflected images simultaneously. The relative strength of each image depends on the brightness of each scene. When we look out of a window during the day, the outdoor image overwhelms the indoor image to the point where the reflected indoor image is rarely seen. However, at night, the windows act as a dark mirror. Many people find this "black hole effect" unpleasant. Also, since about 90 percent of the light striking the windows is lost, large window areas create an inefficient lighting system at night. The best solution is to have movable window coverings such as curtains, shades, or venetian blinds that can be used as sunshades during the day and light reflectors at night.
7. *Computer monitors*. The tasks of looking at computer monitors is now almost universal. The glossy surface and vertical screen make veiling reflections a problem. Avoid bright light sources or bright surfaces behind the operator (Fig. 12.11j). If it is not possible to eliminate these offending light sources, place a partition behind the operator. Indirect lighting from large areas of ceiling and walls works quite well, as does direct, almost vertical lighting from the ceiling. Unlike most tasks, more light makes it harder to see the screen. The best approach is to have low-level ambient illumination of about 10 footcandles (100 lux) and task lights for any printed material that needs to be referred to.

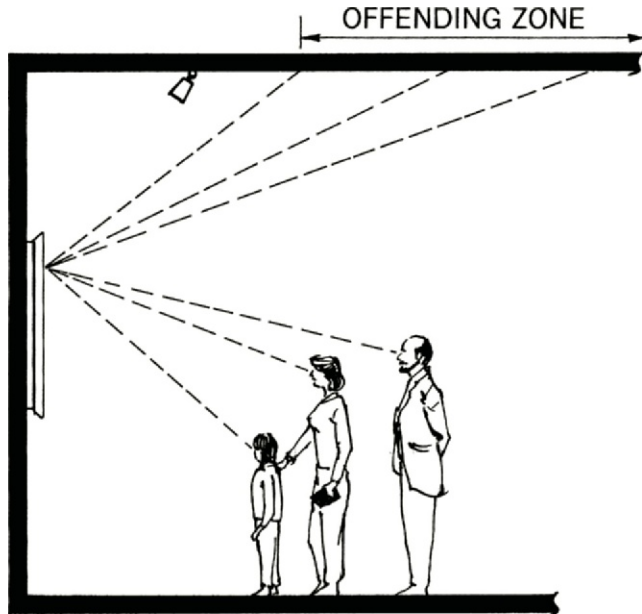


Figure 12.13h Accent lighting must be placed in front of the offending zone.

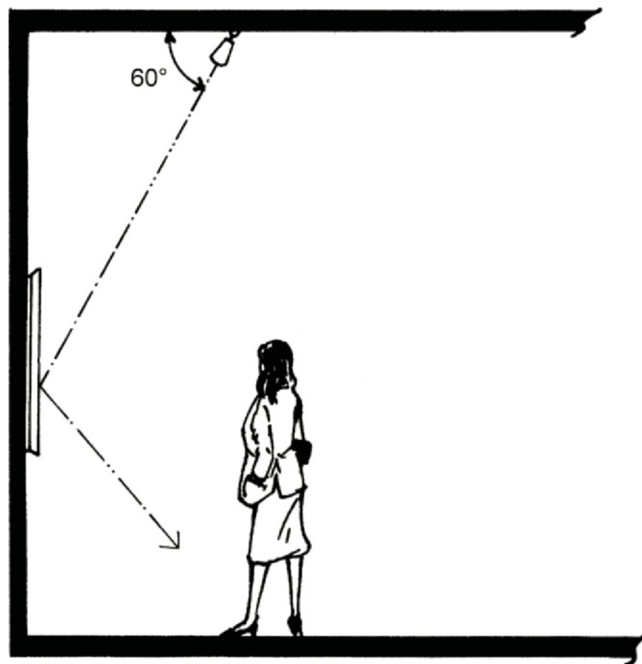


Figure 12.13i Under normal conditions, a 60° fixture aiming angle is satisfactory.



Figure 12.13j These two photos are taken from outdoors looking through the storefront of a sporting goods store. With normal glass (right) the reflections of the bright outdoors overwhelm the transmitted image. However, when the storefront is replaced with special antireflective coating glass (left), the reflected image almost disappears. (Courtesy of Schott Co.)

12.14 BIOLOGICAL NEEDS

A good lighting design must address not only the previously mentioned requirements for visual performance, but also the biological needs shared by all human beings, independent of culture and style. These needs relate to the biological requirements of orientation, stimulation, sustenance, defense, and survival. The following list of biological needs is largely based on the book *Perception and Lighting as Formgivers for Architecture*, by William Lam (1992):

1. *The need for spatial orientation*. The lighting system must help define slopes and changes of level. It must also help people know where they are and where to go. For example, an elevator lobby or reception area might be brighter than the corridor leading to it because people's attention is drawn to bright lights (Fig. 12.14a). Windows are very helpful in relating one's position inside a building to the outside world.
2. *The need for time orientation*. Jet lag is a result of internal clocks being out of synchronization with what the eyes see. The internal clock might expect darkness and the time for sleep, while the eyes experience bright sunshine. Melatonin might be produced or suppressed at the wrong times during a person's circadian rhythm. The least stress occurs when the eyes see what the internal clocks expect. For example, views of the exterior through clear glazing give people the feedback on the progress of time that their internal clocks seem to need.
3. *The need to understand structural form*. The need to understand the physical world is frustrated by lighting that contradicts the physical reality, by excessive darkness or by excessively diffuse lighting.



Figure 12.14a An elevator lobby or reception area can become the focus for direction by making it brighter than the corridor leading to it. (Photograph courtesy of Hubbell/Lighting Division.)

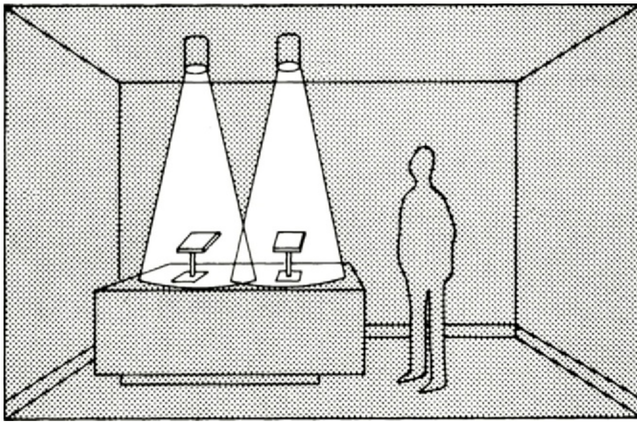


Figure 12.14b Important areas can be highlighted, while less important areas can receive subdued illumination. (From *Architectural Graphic Standards*, Ramsey/Sleeper, 8th ed. John R. Hoke, editor, © John Wiley & Sons. Inc., 1988.)

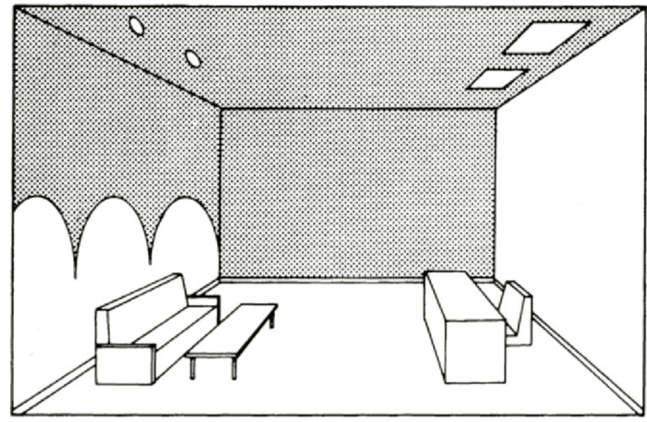


Figure 12.14c Changing light levels can help define personal space. (From *Architectural Graphic Standards*, Ramsey/Sleeper, 8th ed. John R. Hoke, editor, © John Wiley & Sons, Inc., 1988.)

Directional light gives form to objects, while diffuse light tends to flatten their appearance. The sculpture in Figure 12.13b is well modeled by the mostly directional light, while it loses its three-dimensional quality when illuminated by completely diffuse lighting (Fig. 12.13d). Fog and luminous ceilings both create this excessively diffuse type of lighting.

4. *The need to focus on activities*. To prevent information overload, the brain has to focus its attention on the most important aspects of its environment and largely ignore the rest. The lighting can help by creating order and by highlighting the areas and activities that are most relevant. Low illumination for the less important areas is just as important as highlighting (Fig. 12.14b).
5. *The need for personal space*. Light and dark areas in a large room can help define the personal space of each individual (Fig. 12.14c). Uniform lighting tends to reduce individuality, while local or furniture-integrated lighting emphasizes personal territory. A study by Steelcase, the office furniture company, showed that about 75 percent of office workers would like to control their own lighting. Personal lighting fixtures that can be adjusted are an easy way to satisfy this desire to control one's environment.
6. *The need for cheerful spaces*. Dark walls and ceilings create a cave-like atmosphere (Fig. 12.10c). This gloom can be caused by specifying dark surfaces, low illumination levels, or excessively vertical light. However, a dark restaurant with candlelight is not gloomy because we expect it to be dark. A space is, therefore, gloomy only if we expect it to be bright and it is not. Although small patches of sunlight can be especially welcome in the winter, direct sunlight must be kept off the task to prevent excessive brightness ratios at the center of vision. Gloom can also be created without dark surfaces. Most people find the lighting from an overcast rainy day to be quite gloomy. An all-indirect-lighting scheme, as shown in Figure 12.14d, can create this same dull, dreary appearance. Instead, a combination of direct, indirect, and accent lights creates a most interesting and cheerful design (Fig. 12.14e).
7. *The need for interesting visual input*. Dull spaces are not made interesting just by increasing the light levels. A very barren space might be interesting for a short period, when it is first perceived, but it will not remain interesting for long. Furthermore, there is a need to look up occasionally from one's work and to scan the environment. Interesting objects, such as windows, people, paintings, sculpture, and plants, can act as visual rest centers. Viewing distant objects allows the eye muscles to relax.
8. *The need for order in the visual environment*. When order is expected but not present, we perceive chaos. For example, when the lighting fixtures in the ceiling have no relationship with the structure, we find the design disturbing (Fig. 12.14f).
9. *The need for security*. Darkness is a lack of visual information. In a situation in which we expect danger, this lack of information causes fear. Dark alleys, dark corners, and shadows from trees are best eliminated by numerous closely spaced streetlights and not by a few very bright lights. Just as bright areas appear brighter if they are adjacent to dark areas, dark areas are darker if they are adjacent to bright areas. Low brightness ratios are best. Light-colored buildings help



Figure 12.14d An all-indirect-lighting scheme creates a feeling of gloom. (Photograph by James Benya.)

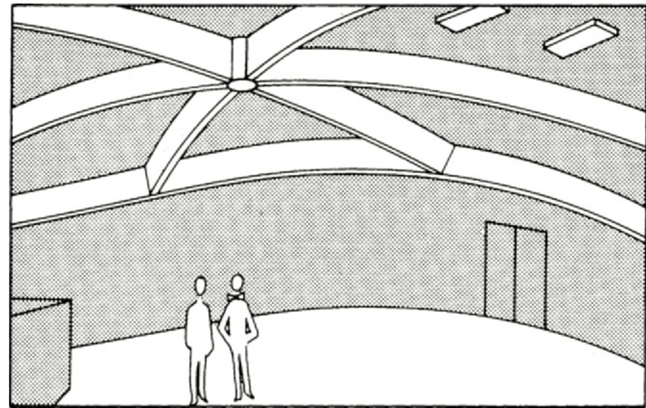


Figure 12.14f When the lighting fixture pattern is not in harmony with the structure, the need for order is frustrated. (From *Architectural Graphic Standards*, Ramsey/Sleeper, 8th ed. John R. Hoke, editor, © John Wiley & Sons, Inc., 1988.)



Figure 12.14e A cheerful and interesting lighting design is achieved by the combination of direct, indirect, and accent lights. (Photograph by James Benya.)



Figure 12.14g Light-colored buildings can be a source of gentle, diffused area lighting at night. (Courtesy of Spaulding Lighting, Inc.)

greatly by reflecting diffuse light into dark corners (Fig. 12.14g).

Most lighting systems that satisfy these biological needs automatically also satisfy the needs of the visual tasks mentioned before.

12.15 LIGHT AND HEALTH

In northern latitudes, where winter days are short, depression is more common in the winter than in the summer. Dr. Alfred J. Lewy discovered that light therapy could help some patients who become depressed during the short winter days. This illness is now called **seasonal affective disorder (SAD)**.

Research has shown that bright light (more than 150 footcandles or 1500 lux) through the eyes will cause the pineal gland in the brain to stop making melatonin, which is produced whenever people are in the dark. High melatonin levels cause drowsiness, while low levels produce alertness; thus, melatonin plays a critical part in our circadian cycles. There is also increasing evidence that low melatonin production at night contributes to breast and prostate cancers.

Other recent research has discovered new light-sensitive cells in the retina that have no function in seeing. It is believed that these special ganglion cells directly affect the endocrine cycle, which in turn controls the circadian cycle.

Many industrial accidents occur during the night shift. It is now believed that many of these accidents, as well as jet lag, result from drowsiness caused by activity at a time when our internal clocks tell us to be sleeping. Research in light therapy shows promising developments in several areas: fighting SAD depression,

making people more alert at night, regulating sleep cycles for older people, and alleviating the problem of jet lag. Thus, people should sleep in very dark rooms to encourage high melatonin production and then be exposed to high levels of light after getting up in order to suppress the melatonin production. Nightlights should emit red light because the blue end of the spectrum has a greater impact on the circadian rhythms. The easiest way for architects to supply bright light is with views of the bright outdoors and with the utilization of high levels of daylight (about 250 footcandles or 2500 lux).

Other photobiological effects of light exist besides melatonin suppression. Excessive ultraviolet (UV) radiation can cause serious burns to skin and eyes, blindness, and, in some cases, skin cancer. For this reason, most lamps sold in the United States have glass covers that absorb most of the damaging UV radiation emitted by source lamps. However, excessive visible light, especially blue and violet light, can also cause serious eye and skin burns. Light also plays a role in a variety of body functions, and it is used in the treatment of such diseases as hyperbilirubinemia, psoriasis, and vitamin D deficiency (rickets).

A few people seem to get headaches from the 120 flashes per second that fluorescent lights operating with magnetic ballasts create (see Chapter 14). This problem is easily solved by switching to electronic ballasts, which have the additional benefit of increased efficiency.

12.16 THE POETRY OF LIGHT

The previous objective discussion of lighting principles was both necessary and useful. A full understanding of lighting also requires a poetic perspective. Richard Kelly, who was one of the foremost lighting designers, fully understood the role of poetry in design conceptualization. His own words say it best:

In dealing with our visual environment, the psychological sensations can be broken down into three elements of visual design. They are focal glow, ambient luminescence, and the play of brilliants.

Focal glow is the campfire of all time . . . the welcoming gleam of the open door . . . the sunburst through the clouds. . . . The attraction of the focal glow commands attention and creates interest. It fixes gaze, concentrates the mind, and tells people what to look at. It separates the important from the unimportant. . . .

Ambient luminescence is a snowy morning in open country. It is twilight haze on a mountaintop . . . a cloudy day on the ocean . . . a white tent at high noon. . . . It fills people with a sense of freedom of space and can suggest infinity. . . .

The background of ambient luminescence is created at night by fixtures that throw light to walls, curtains, screens, ceilings and over floors for indirect reflection from these surfaces.

Play of brilliants is the aurora borealis. . . . Play of brilliants is Times Square at night. . . . It is sunlight on a tumbling brook. . . . It is a birch tree interlaced by a motor car's headlights. Play of brilliants is the magic of the Christmas tree . . . the fantasy excitement of carnival lights and restrained gaiety of Japanese lanterns. . . . A play of brilliants excites the optic nerves, stimulates the body and spirit, and charms the senses.

12.17 RULES FOR LIGHTING DESIGN

The following rules are for general lighting principles. Specific rules for electric lighting and daylighting will be given in the next two chapters.

1. First, establish the lighting program by fully determining what the seeing task is in each space. For example, is the illumination mainly for vertical or horizontal surfaces? Are colors very important? Does the task consist of very fine print? Will daylighting be used to reduce the need for electric lighting?
2. Illuminate those things that we want or need to see. Since this usually includes the walls and some furnishings, the light reflected from these surfaces can supply much of the required illumination. Except for decorative light fixtures, such as chandeliers, we usually want to see objects, not light sources.
3. Quality lighting is largely a problem of geometry. Direct glare and veiling reflections are avoided mainly by manipulating the geometry between the viewer and the light source. The main light source should never be in front of the viewer. Glare can also be prevented by baffling the light sources from normal viewing angles. Baffles can be louvers, eggcrates, or parts of a building. With indirect lighting, the ceiling becomes a large-area, low-brightness source with minimal glare and veiling reflections (Fig. 12.17a).
4. In most situations, the best lighting consists of a combination of direct and diffuse light. The resulting soft shadows and shading enable us to fully understand the three-dimensional quality of our world.
5. "Darkness is as important as light: it is the counterpoint of light—each complements the other" (Hopkinson). Avoid, however, very large brightness ratios that force the eye to readapt continually.
6. An object or area can be highlighted by either increasing its brightness or reducing the brightness of the immediate surroundings. The absolute brightness



Figure 12.17a Direct glare from bright lighting fixtures is not a problem with an indirect lighting system. The whole ceiling becomes a low brightness source. The uplights are part of the office furniture. (Courtesy of and © Peerless Lighting Corporation.)



Figure 12.17b This artwork is highlighted by reducing the background brightness. MIT Chapel by Eero Saarinen.

matters little. What does matter is that the brightness ratio should be about 10 to 1 (Fig. 12.17b) for the purpose of highlighting.

7. Paint is one of the most powerful lighting tools. In most cases, light colors are desirable, and with indirect lighting, the most reflective white paint is almost mandatory. This is one of the most economical lighting tools; usually it costs nothing because paint or some finish is specified anyway. Dark colors should be considered only when drama rather than the performance of visual tasks is the goal for the lighting design. Important examples of places where drama is the goal are certain museums and theaters; here the highlighting of objects or the stage, respectively, draws the viewer's attention.

   Dark paint is often used to hide the clutter of pipes, ducts, and beams where a suspended ceiling is not possible or desirable. In such a case, direct lighting that does not depend on reflections off the ceiling should be used. Remember, you cannot make a room with dark finishes look light.
8. Use daylighting wherever possible. Most people prefer the quality and variety of daylight. They especially desire and need the views that often accompany daylighting. Eye muscles are relaxed only when we look at a distant object. There is evidence that both health and productivity benefit from the use of daylight in buildings. Recent research has shown that children perform better in daylit than in electrically lit classrooms.
9. Flexibility and quality are more important than the quantity of light, and these goals are most easily achieved with task/ambient lighting. Flexible task lights provide many benefits: they are energy efficient, they provide very high-quality light, they work well with computers, they respond well to individual users' needs, and they provide user satisfaction because they allow occupants to control their own lighting environment. The task/ambient lighting system also provides a low level of background lighting for the whole space.

12.18 CAREER POSSIBILITIES

Because lighting is so important and complex, a new profession of lighting designers has emerged. Since the emphasis is on both functional design and aesthetics, architects have

a good appreciation and background for this field. With some additional education and experience, an architect can become a lighting consultant, working on a wide variety of projects with some of the world's most prominent architects and interior designers. For more information, contact the International Association of Lighting Designers (IALD) (www.iald.org). For a master's degree in lighting, consider the Lighting Research Center at Rensselaer Polytechnic Institute (www.lrc.rpi.edu).

Since 1998, the National Council for the Qualifications for the Lighting Professions (NCQLP) has administered a national certification test for lighting designers. Architects qualify for taking the test that leads to the title "Lighting Certified" (LC). See www.ncqlp.org for information about the test.

12.19 CONCLUSION

The importance of quality over quantity cannot be overemphasized, because for too long the general opinion has been "more is better." It is a bit strange that this attitude was so widely held, because we do not hold it in regard to the other senses. We do not appreciate sound according to its loudness. The difference between noise and music is certainly not its volume. We do not appreciate touch by its hardness. And we do not appreciate smell or taste by its strength. In each case, a minimum level is required, but above that, it is quality and not quantity that counts. Our sense of sight is no different in this regard.

Ignoring quality has always impaired visual performance. Often, the detrimental effects are not even recognized. There is, however, a very dramatic example in which the impairment of visual performance could not be ignored. The Houston Astrodome was built with translucent plastic bubbles over a very interesting steel structure, as seen in Figure 12.19a. The illumination level was high enough indoors to allow grass to grow on the playing field. However, high-flying balls could not be seen against the visual "noise" of the structure. The problem was solved by painting over the skylights and using electric lights even during the day. Since the grass then died, it was replaced by Astroturf. This disaster occurred because lighting was considered only as a problem of quantity and not as a problem of quality that must be integrated with the architecture. A pneumatic structure, on the other hand, solves the lighting problem in a well-integrated manner (Fig. 12.19b). It creates a neutral background for the ball, it allows soft daylight to enter, and at night it reflects low-brightness light from electric light sources.

To best satisfy all the biological and activities needs, one must usually integrate daylighting and electric lighting. With the basic concepts of this chapter and the more specific information of the next two chapters on daylighting and electric lighting, designers should be able to design a high-quality lighting environment that will satisfy the environmental, biological, psychological, aesthetic, and activity needs of the occupants.

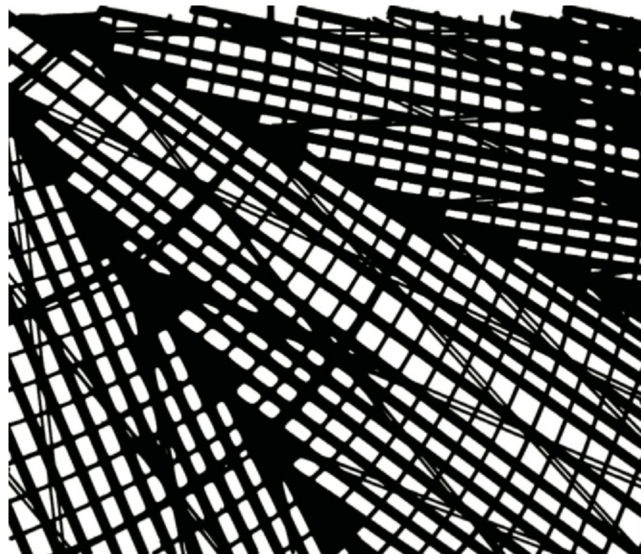


Figure 12.19a The structure and skylights of the Houston Astrodome had created an interesting visual pattern, which, unfortunately, became very strong visual noise when people tried to see a high-flying ball.



Figure 12.19b Pneumatic structures with translucent membranes are an example of well-integrated designs. These structures provide daylight without visual noise, and at night they work well with indirect lighting. (Courtesy of Tensar Structures, Inc.)

KEY IDEAS OF CHAPTER 12

1. The rate at which light is emitted from a source is measured in lumens, while the intensity in any direction is called candlepower and is measured in candelas.
2. Illumination (illuminance) is measured in footcandles (lux).
3. Luminance is measured brightness, and its units are candelas per square foot (candelas per square meter).
4. The reflectance factor (reflectance) describes how much of the light falling on an object is reflected.
5. Light can be reflected in a specular, diffuse, or mixed fashion.
6. The color of an opaque object is the result of both the spectrally selective reflections of the object and the spectral composition of the light source.
7. The consistency of white light can be described by the correlated color temperature (CCT) and measured in kelvin (K), by the color-rendering index (CRI), or by a spectral-energy distribution diagram (SED), which is also known as a spectral-power distribution diagram (SPD).
8. The iris controls the size of the pupil to adjust the amount of light falling on the retina.
9. Lighting should be designed for what people perceive, not for what meters measure.
10. The performance of a visual task is a nonlinear function of brightness (i.e., a little light is very helpful, but a lot of light is only slightly better).
11. Use IESNA (Illuminating Engineering Society of North America) recommendations for task lighting, one-third of those levels for general illumination, and only one-third of those levels for circulation areas (i.e., one-ninth of task levels). Use somewhat higher levels for daylighting in summer, and use much higher levels for daylighting in winter.
12. Rules for quality lighting:
    a. Control brightness ratios.
    b. Avoid glare.
    c. Avoid veiling reflections.
13. Don't forget the poetry of light:
    a. Focal glow.
    b. Ambient luminescence.
    c. Play of brilliants.
14. Rules for lighting design:
    a. Determine the nature of the visual task.
    b. Illuminate the things that we want or need to see.
    c. Quality lighting is largely a problem of geometry.
    d. Darkness is as important as light.
    e. Use light-colored finishes whenever possible.
    f. Use efficient electric lighting.
    g. Use daylighting wherever possible.
    h. Flexibility and quality are much more important than the quantity of light above the minimum task-illumination level. Use task/ambient lighting.

References

Boyce, P. R. *Human Factors in Lighting*, 2nd ed.

Hopkinson, R. G. *Architectural Physics*: *Lighting*, 1963.

Lam, W. M. C. *Perception and Lighting as Formgivers for Architecture*. New York: Van Nostrand Reinhold, 1992.

Resources

FURTHER READING

(See the Bibliography in the back of the book for full citations.)

Boyce, P. R. *Human Factors in Lighting*, 2nd ed.

Brown, G. Z., and M. DeKay. *Sun, Wind, and Light: Architectural Design Strategies*, 2nd ed.

Cuttle, C. *Lighting by Design*.

DiLaura, D. *A History of Light and Lighting*.

Egah, M. D., and V. Olgyay. *Architectural Lighting*, 2nd ed.

Flynn, J. E., et al. *Architectural Interior Systems: Lighting, Acoustics, and Air-Conditioning*.

Futagawa, Y., ed. *Light and Space: Modern Architecture*.

Gordon, G., and J. L. Nuckolls. *Interior Lighting for Designers*, 4th ed.

Grosslight, J. *Light, Light, Light: Effective Use of Daylight and Electric Lighting in Residential and Commercial Spaces*, 3rd ed.

IESNA Lighting Handbook, 10 th ed. 2011.

Karlen, M., and J. Benya. *Lighting Design Basics*.

Kwok, A., and W. Grondzik. *The Green Studio Handbook: Environmental Strategies for Schematic Design*.

Lam, W. M. C. *Perception and Lighting as Formgivers for Architecture*.

Millet, M. S. *Light Revealing Architecture*.

Moore, F. *Environmental Control Systems*.

Schiler, M. *Simplified Design of Building Lighting*.

Steffy, G. R. *Architectural Lighting Design*, 2nd ed.

———. *Time-Saver Standards for Architectural Lighting*.

Stein, B., J. S. Reynolds, W. T. Grondzik, and A. G. Kwok. *Mechanical and Electrical Equipment for Buildings*, 10th ed. A basic resource.

ORGANIZATIONS

(See Appendix K for full citations.)

California Lighting Technology Center, www.cltc.ucdavis.edu

IESNA (Illuminating Engineering Society of North America), www.iesna.org

International Association of Lighting Designers (IALD), www.iald.org

LBNL (Lawrence Berkeley National Laboratory), www.eande.lbl.gov

Lighting Design Lab, www.northwestlighting.com

Lighting Research Center-Rensselaer Polytechnic Institute, www.erc.rpi.edu

CHAPTER 13

DAYLIGHTING

We were born of light. The seasons are felt through light. We only know the world as it is evoked by light. . . . To me natural light is the only light, because it has mood—it provides a ground of common agreement for man—it puts us in touch with the eternal. Natural light is the only light that makes architecture architecture.

Louis I. Kahn

I'd put my money on the sun and solar energy. What a source of power! I hope we don't wait 'til oil and coal run out before we tackle that.

Thomas A. Edison

13.1 HISTORY OF DAYLIGHTING

Until the second half of the twentieth century, when fluorescent lighting and cheap electricity became available, the history of daylighting and the history of architecture were one. From the Roman groin vault (see Fig. 1.3c), to the Crystal Palace of the nineteenth century, the major structural changes in buildings reflected the goal of increasing the amount of light that was collected. Because artificial lighting had been both poor and expensive until then, buildings had to make full use of daylight.

Gothic architecture was primarily a result of the quest for maximum window area. Only small windows were possible when a barrel vault rested on a bearing wall. The Roman groin vault supplanted the barrel vault partly because it allowed large windows in the vaulted spaces (Fig. 13.1a). Gothic groin vaulting with flying buttresses provided a skeleton construction that permitted the use of very large windows (Fig. 13.1b).

Large and numerous windows were a dominant characteristic of Renaissance architecture. Windows dominated the facade, especially in regions with cloudy climates, such as England. The increase in window size was so striking that one English manor was immortalized in rhyme: "Hardwick Hall, more window than wall" (Fig. 13.1c). Bay windows, too, became very popular (see Fig. 16.2e). Although the facades of such Renaissance palaces were designed to give the impression of great massive structures, their E- and H-shaped floor plans provided for their ventilation and daylight requirements. As a matter of fact, such shapes were typical of floor plans for most large buildings until the twentieth century (Fig. 13.1d).

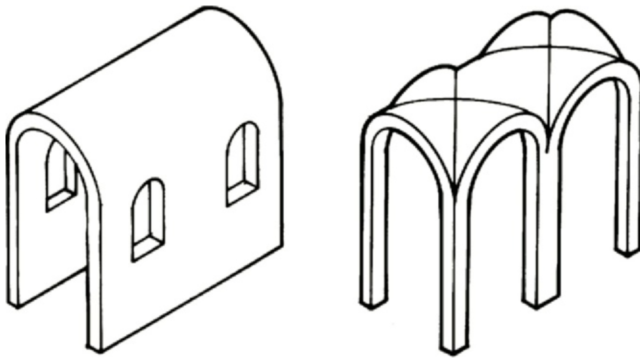


Figure 13.1a Because few windows were possible in the massive bearing walls required to support the Romanesque barrel vault, the Gothic builders turned to the Roman groin vault. (From *Architectural Lighting*, 1987. © Architectural Lighting. Reprinted Courtesy of Cassandra Publishing Corporation, Eugene, OR.)



Figure 13.1c Hardwick Hall, Derbyshire, England, 1597, "more window than wall." (From *Mansions of England in Olden Times*, by Joseph Nash, Henry Sotheran & Co., 1871.)



Figure 13.1b Groin vaulting and flying buttresses allowed Gothic cathedrals to have windows where there had been walls.

These buildings or their wings were rarely more than 60 ft (18 m) deep so that no point would be more than 30 ft (9 m) from a window. High ceilings with high windows allowed daylight to reach about 30 ft (9 m) in from the exterior walls, while today's lower ceilings allow daylight to reach in only about 15 ft (4.5 m).

During the nineteenth century, all-glass buildings became possible because of the increased availability of glass combined with the new ways of using iron for structures. The Crystal Palace by Paxton is the most famous example (see Fig 4.2d and the galleria in Fig. 4.2c).

More modest amounts of glass and iron could be found in many buildings of the day. The Bradbury Building, designed around a glass-covered atrium, is a precursor for many of today's office buildings (Fig. 13.1e).

In older neighborhoods of many cities, such as New York City, it is still possible to find sidewalks paved with glass blocks that allow daylight to enter basements. New York City enacted zoning codes to ensure minimum levels of daylighting. In England, laws that tried to ensure access to daylight date back as far as the year 1189.

The masters of twentieth-century architecture continued to use daylight for both functional and dramatic purposes. In New York's Guggenheim Museum, Frank Lloyd Wright used daylight to illuminate the artwork both with indirect light from ribbon windows and with light from an atrium covered by a glass dome (Figs. 13.1f and 13.1g). In the Johnson Wax Administration Building in Racine, Wisconsin, he created a space with no apparent upper boundaries by letting daylight enter continuously along the upper walls and the edge of the roof. Daylight also enters through skylights around the mushroom columns (Figs. 13.1h and 13.1i).

Le Corbusier created very dramatic effects with the splayed windows and light towers of the chapel at Ronchamp (Figs. 13.1j, 13.1k, and 13.1l). Eero Saarinen used a fascinating form of daylight in the MIT chapel. A skylight over the altar was fitted with a black eggcrate so that only vertical light could enter the chapel. This vertical light was then reflected into the room by a sculpture consisting of small brass reflectors like leaves on a tree (see Fig. 12.17b).

This short history demonstrates what an important role daylight has had in architecture. We will look at more examples after we discuss some of the basic daylighting concepts.

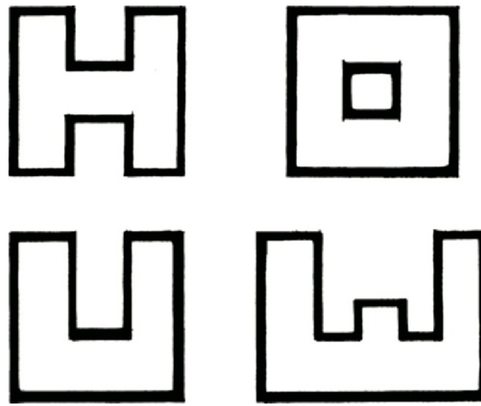


Figure 13.1d These were the common floor plans for large buildings prior to the twentieth century because of the need for light and ventilation.



Figure 13.1e The Bradbury Building, Los Angeles, 1893, has a glass-covered atrium as the circulation core. Delicate ironwork allows light to filter down to the ground level. The building was cooled by natural ventilation. Air entered exterior windows, passed through transoms and interior windows facing the atrium, and then left through mechanically operated hopper windows just below the skylight.



Figure 13.1f The Guggenheim Museum, New York City, 1959, by Frank Lloyd Wright uses a glass-domed atrium for diffused daylighting.



Figure 13.1g Continuous strip windows bring additional daylight to the Guggenheim Museum gallery space. (Courtesy of New York City Convention and Visitors Bureau, Inc.)



Figure 13.1h The Johnson Wax Administration Building, Racine, Wisconsin, 1939, was designed by by Frank Lloyd Wright. Note the skylights between the mushroom columns, as well as the glazing at the junction of roof and walls. The two circular shafts (center left) are fresh-air intakes ("nostrils" as Wright called them). (Courtesy of SC Johnson Wax.)



Figure 13.1i Glazing dematerialized the upper walls and ceiling of the Johnson Wax Administration Building. (Courtesy of SC Johnson Wax.)



Figure 13.1j In Notre Dame du Haut at Ronchamp, France, 1955, Le Corbusier used thick walls with splayed windows, colored glass, and light scoops to bring carefully controlled light into the interior. (Photograph by William Gwin.)



Figure 13.1k Interior of Notre Dame du Haut. (Photograph by William Gwin.)

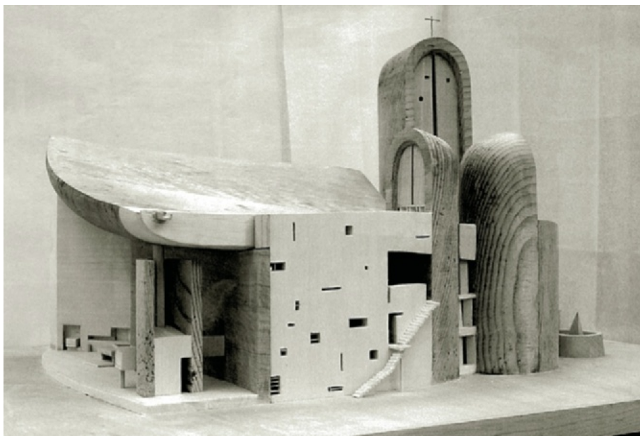


Figure 13.1l Slit openings in the light scoops are seen in this rear view of a model of Notre Dame du Haut built by Simon Piltzer at the University of Southern California in Los Angeles.

13.2 WHY DAYLIGHTING?

Daylighting became a minor architectural issue as we entered the second half of the twentieth century because of the availability of efficient electric light sources; cheap, abundant electricity; and the perceived superiority of electric lighting. Perhaps the most important advantage of electric lighting was—and still is—the ease and flexibility it permitted in floor-plan design by enabling designers to ignore window locations.

Supplying adequate daylight to work areas can be quite a challenge while electric lighting is so much simpler. It offers consistent lighting that can be easily quantified, but it has some serious drawbacks.

The energy crisis of the mid-1970s led to a reexamination of the potential for daylighting. At first, only the energy implications were emphasized, but now daylighting is also valued for its aesthetic possibilities and its ability to satisfy biological and human needs.

According to the Department of Energy (DOE), lighting consumes about 25 percent of the electricity consumed by all buildings and 40 percent by commercial buildings. About half of all that electricity could be saved by daylighting. For some building types, such as offices, schools, libraries, and museums, daylighting can save even more energy. For example, in buildings such as schools and offices about 70 percent of the lighting energy can be saved through daylighting. Since in these kinds of buildings lighting is the main energy user (Fig. 13.2a), daylighting will significantly reduce the total energy consumption. It gets even better. Daylighting can also reduce the heating and cooling energy consumption because it can be cooler than electric lighting in the summer, and it can passively heat a building in the winter.

Even today, much of the nation's work is still done during daylight hours. Most people work about 2000

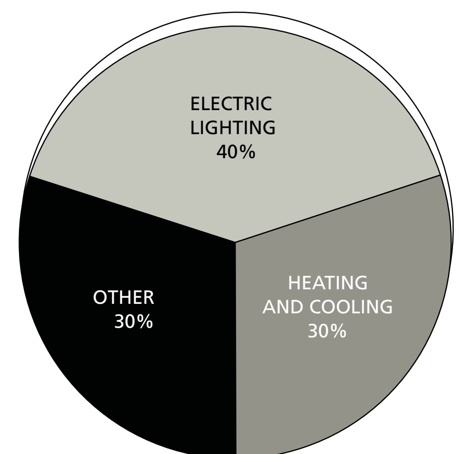


Figure 13.2a Typical distribution of energy use for buildings such as offices, schools, and many industrial facilities.

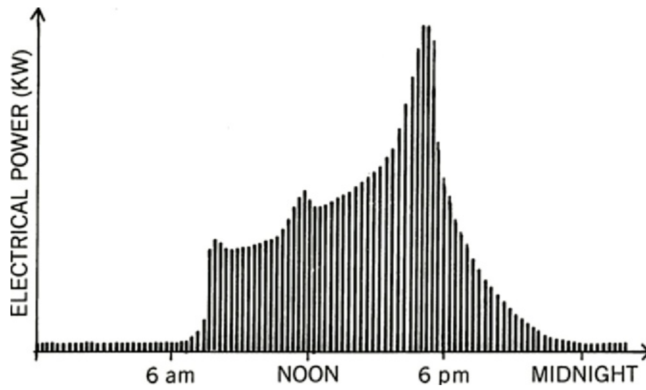


Figure 13.2b In most parts of the country and the world, the maximum demand for electricity in an office building occurs on a hot summer afternoon, when daylighting is plentiful.

hours each year (40 hours/week × 50 weeks), and over 80 percent of those hours occur when useful daylight is available.

There is another energy-related factor in using daylight, and it is usually the more important factor in terms of money. Figure 13.2b shows the rate at which energy is used in a typical office building during a sunny summer day. The horizontal axis represents time and the vertical axis describes the rate at which electricity is used (kilowatts). The greatest annual electrical demand usually occurs during sunny summer afternoons, when the air-conditioning is working at full capacity. Since the sun creates this maximum cooling load, it simultaneously also supplies the maximum amount of daylight. Consequently, some or most of the electric lights, which consume about 40 percent of the total energy, are then not needed. The maximum demand for electrical power can, therefore, be reduced up to 40 percent by the proper utilization of daylighting.

Electric power plants are, and must be, built and sized not for the total energy used but for the maximum demand. Heavy consumers of electricity are, therefore, charged not only for the total energy they use, but also for the maximum demand they make on the utility. For such users (e.g., large office buildings, schools, and factories), daylighting can significantly reduce the cost of electricity because of both the reduced energy use and the reduced "demand charge." Much of the extra cost for the daylighting design can be offset by savings in demand charges. Society and the planet also benefit if the demand for electricity can be reduced, because fewer electric power plants will have to be built in the future. The energy and electrical demand savings of daylight are greatly underutilized, in part because most designers and building owners underestimate its potential (Fig. 13.2c).

The dynamic nature of daylight is now seen as a virtue rather than a liability. It satisfies the biological need to respond to the natural rhythms of the day. The generally slow but occasionally dramatic changes in the quality and intensity of natural light can be stimulating.

Recent research by the Heschong-Mahone Group (www.h_m_g.com) showed an improvement of about 20 percent in the performance of students in daylit schools over standard schools. The same researchers also discovered that daylighting can increase retail

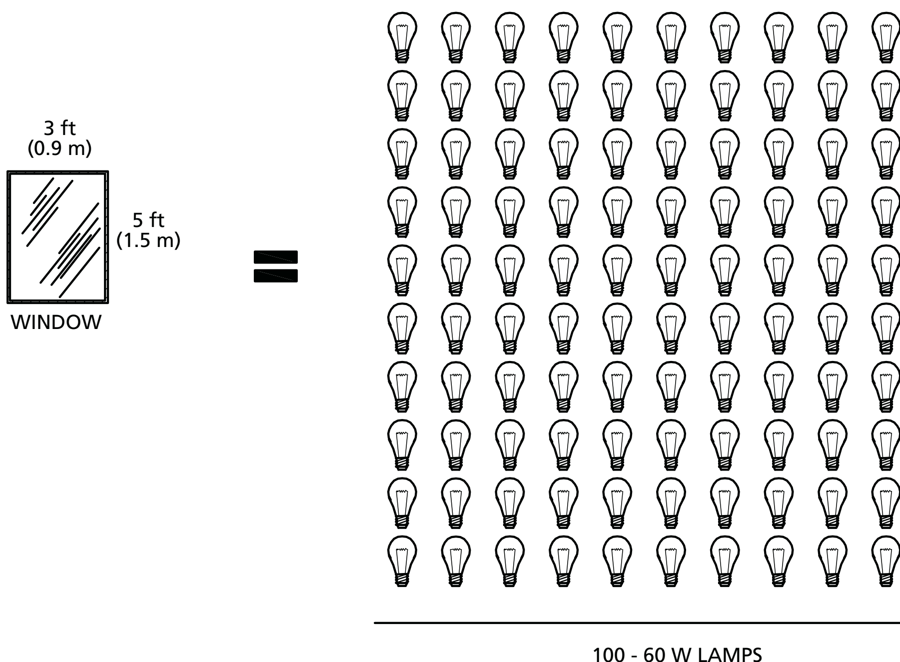


Figure 13.2c To get an indication of the energy and electrical demand savings possible with daylighting, this figure shows how many 60 W incandescent lamps would be required to produce the same amount of light as a 3 × 5 ft (0.9 × 1.5 m) window. (After Rocky Mountain Institute.)

Table 13.2 LEED Points for Daylighting

Strategy	Points
75% of building is daylit	1
90% of building is daylit	2
Views for 90% of occupants	1
Daylighting contributes to total energy efficiency of building	Up to 10

sales by about 3 percent. Although 3 percent seems very small, the amount of money involved is tremendous and can easily pay for any extra expense of the daylighting design.

Some other countries have long understood the benefits and importance of daylighting. In Europe, building codes require workers to have access to both views and daylighting.

One of the important side effects of daylighting is usually an increase in the number of occupants that have a view to the outdoors. Research has shown that a good view versus no view results in increased productivity, mental function, and memory recall. Research has also shown that hospital patients with good views heal faster than those with no view or a poor view. Consequently, LEED points can be earned by providing views as well as for daylighting (see Table 13.2).

Even when daylighting was completely ignored, architects continued to use plenty of windows for the enjoyment of views, for visual relief, for satisfying biological needs, and for aesthetics. It is an irony that all-glass curtain walls are much used but daylighting is not. Daylighting design does not require increasing the window area, but it does require the careful design of the fenestration for the proper distribution, quantity, and quality of daylighting.

13.3 THE NATURE OF DAYLIGHT

The daylight that enters a window can have several sources: direct sunlight, clear sky, clouds, and reflections from the ground and nearby buildings (Fig. 13.3a). The light from each source varies not only in quantity but also in such qualities as color, diffuseness, and efficacy.

Although sky conditions can be infinitely variable, it is useful to understand daylight from the two extreme conditions: overcast sky and clear sky with sunlight. A daylighting design that works under both of these conditions will also work under most other sky conditions.

The brightness distribution of an overcast sky is typically three times greater at the zenith than at the horizon (Fig. 13.3b). Although the illumination from an overcast day is relatively low (500–2000 footcandles [5000–20,000 lux]), it is still ten to fifty times greater than what is needed indoors.

On a clear day, the brightest part of the sky, which is in the direction of the sun, is about ten times brighter than the darkest part of the sky, which is found at about 90° to the sun (Fig. 13.3c). Under a clear sky, the illumination is quite

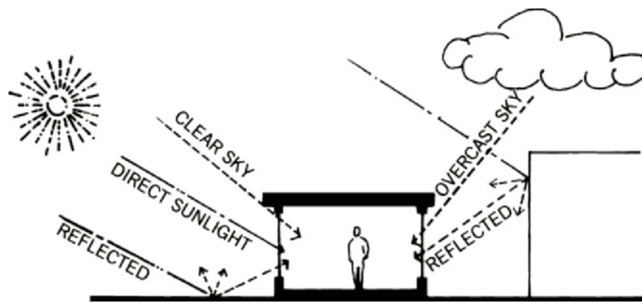


Figure 13.3a The various sources of daylight are shown. Reflected light from light-colored pavement and buildings can be significant. Light reflected from reflective glazing can almost equal direct sunshine.

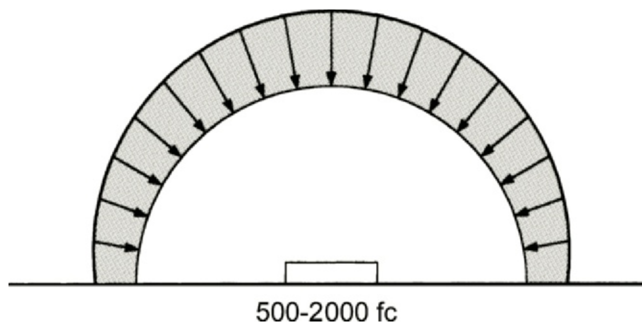


Figure 13.3b The brightness distribution on an overcast day is typically about three times greater at the zenith than at the horizon. (After *Architectural Lighting*, 1987. © Architectural Lighting. Reprinted courtesy of Cassandra Publishing Corporation, Eugene, OR.)

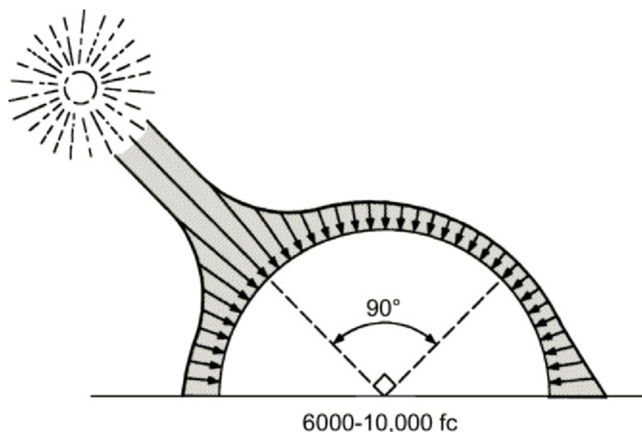


Figure 13.3c The brightness distribution on a clear day is typically about ten times greater near the sun than at the darkest part of the sky. (After *Architectural Lighting*, 1987. © Architectural Lighting. Reprinted courtesy of Cassandra Publishing Corporation, Eugene, OR.)

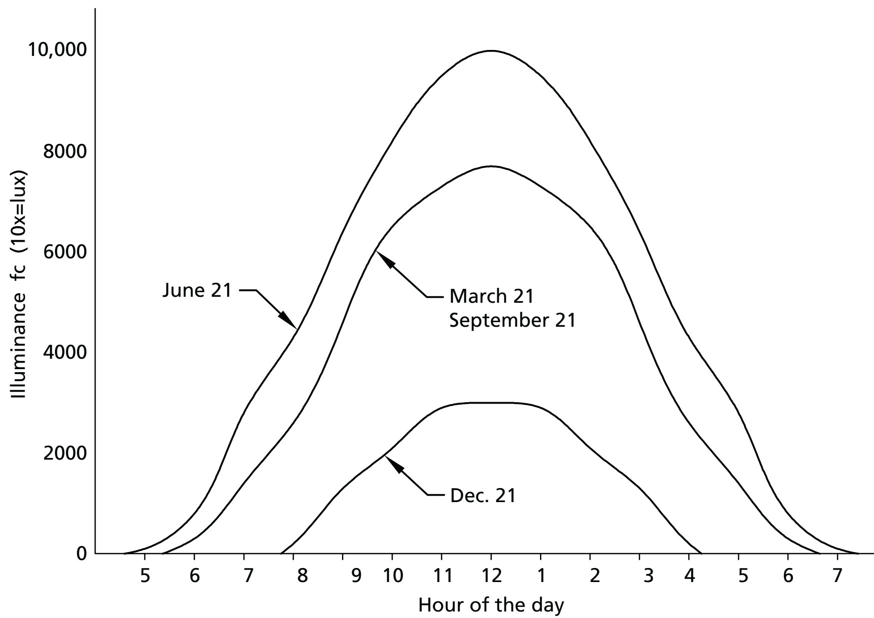


Figure 13.3d Soon after sunrise on a clear day, the illumination will increase rapidly until 12 noon and then decline symmetrically, unless the climate or local conditions modify the pattern. Thus, in most cases, the illumination is very high during most of daylight hours. The values given are for the illumination of a horizontal surface.

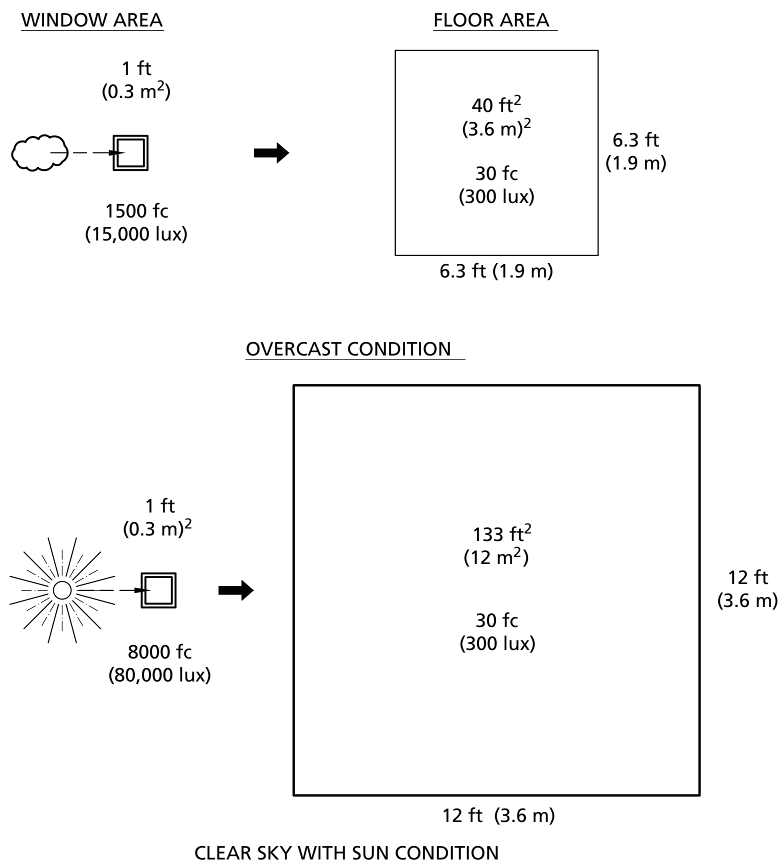


Figure 13.3e Sunlight is such an abundant source of light that a window can illuminate a floor area about 133 times the size of the window if the light is distributed evenly. Even on overcast days, a window can illuminate a floor area about 40 times the size of the window.

high (6,000–10,000 footcandles [60,000–100,000 lux], or 100 to 200 times greater than the requirements for good indoor illumination). For about half of the year and half of each day, the illumination on clear days is above 4000 fc (40,000 lux) (Fig. 13.3d). Under such conditions, a 1 ft^2 (0.09 m^2) window could illuminate approximately 133 ft^2 (12 m^2) of floor area, if the sunlight is evenly distributed. Even on overcast days, that same window could still illuminate about 40 ft^2 (3.6 m^2) of floor area. Thus, well-designed windows and skylights can be quite small (Fig. 13.3e).

The main difficulty with the clear sky is the challenge of direct sunlight, which is not only extremely bright but is continually changing direction. Consequently, to understand clear-day illumination, it is necessary to also understand solar geometry, as explained in Chapter 6.

In most climates, there are enough days of each sky condition to make it necessary to design for both conditions. The main exceptions are parts of the Pacific Northwest, where overcast skies predominate, and the Southwest, where clear skies predominate. Under overcast skies, the main challenge for the designer is one of quantity, while for clear-sky conditions the challenge is one of quality.

The daylight from clear skies consists primarily of the two components of skylight and direct sunlight. The light from the blue sky is diffuse and of low brightness, while the direct sunlight is very directional and extremely bright. Because of the potential for glare, excessive brightness ratios, and overheating, it is sometimes assumed that direct sunlight should be excluded from a building.

It is also sometimes erroneously believed that direct sunshine is appropriate only for solar heating. Figure 13.6a illustrates the efficacy (lumens/watt) of various light sources. Although direct-beam sunlight has a lower efficacy than skylight, its efficacy is comparable to the best electric

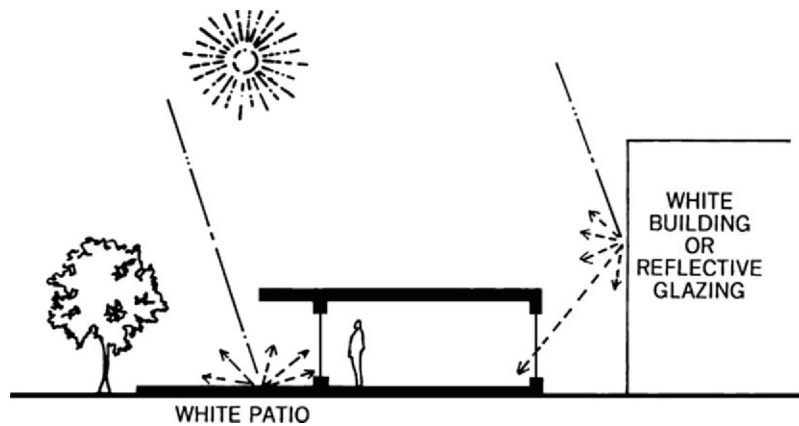


Figure 13.3f Sometimes reflected light is the major source of daylight. Under certain circumstances, a north window can receive as much light as a south window.

Table 13.3 Typical Reflectance Factors

Material	Reflectance (Percent)
Aluminum, reflectors	90–98
Aluminum, polished	70–85
Asphalt	10
Brick, red	25–45
Concrete	30–50
Glass	
Clear or tinted	7
Reflective	20–40
Grass	
Dark green	10
Dry	35
Mirror (glass)	80–90
Paint	
Black	4
White	70–90
Porcelain enamel (white)	60–90
Snow	60–75
Stone	5–50
Vegetation, average	25
Wood	5–40

sources, while its color-rendering ability is superior. Since direct sunlight is an extremely abundant and free source of light, it should be utilized in any daylight design. With the proper design, it can supply high-quality as well as high-quantity daylight.

The light from clear skies, especially the light from the northern sky, is rich in the blue end of the spectrum. While the color-rendering quality of such light is excellent, it is on the cool side (Colorplate 16).

Reflected light from the ground and neighboring structures is often a significant source of daylight (Fig. 13.3f). The reflectance factor of such surfaces is critical in this regard. A white-painted building and reflective glazing can reflect as much as 70 percent of the incident light, while lush green grass will reflect only about 10 percent and mostly green light. Table 13.3 gives the reflectance factors in percent for some common surfaces.

In most climates, daylighting should include sunlighting!

13.4 CONCEPTUAL MODEL*

Direct-beam light can be nicely modeled with arrows, but a diffused source cannot. To understand and to predict the effect of a diffused light source, a different kind of visual model is required. The illumination due to a diffused light source is similar to the concept of mean radiant temperature (MRT) described in Section 3.12. The illuminating effect of a diffused source on a point is a function of both the brightness of the source and the apparent size of the source, which is defined by the exposure angle. Figure 13.4a illustrates the fact that illumination increases with the brightness of the source.

Figures 13.4b–13.4d illustrate how the exposure angle is a function of source size, distance, and tilt. In Figure 13.4b, we see a plan of two desks in a room. The desks are equally far from two windows of equal brightness but different sizes. Obviously, desk B has worse illumination because it has a smaller exposure angle due to the smaller window.

In Figure 13.4c, we see two desks that are both illuminated by the same window. Desk B has again worse illumination because of its smaller exposure angle, which is due to the greater distance to the window.

Finally, in Figure 13.4d, both desks are equally far from the window. Desk B is again more poorly illuminated, but this time the smaller exposure angle is due to the tilt of the source relative to desk B.

In Figure 13.4e, we see a section of the same room. The two main sources of daylight for a point on the table are the sky and the ceiling. Some of the daylight entering the window is eventually reflected off the ceiling, which, in turn, becomes a low-brightness source for the table. The illumination from the ceiling is significant, even though the brightness is low, because of the large apparent size of this source. The sky, despite its smaller apparent size, is the major source of light because it is much brighter than the ceiling. If the walls are of a light color, they will also reflect some light on the table. For simplicity, the contribution of the walls is not shown in Figure 13.4e.

*This section is based on material from *Concepts and Practice of Architectural Daylighting*, by Fuller Moore (1985).

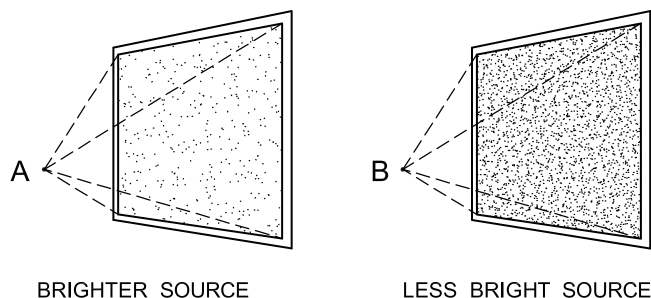


Figure 13.4a The illumination of a point by a diffuse source like a window is a function of both the brightness of the source and the exposure angle. In this example, the exposure angle (solid angle) has been held constant and only the brightness varied. (After Moore, 1985.)

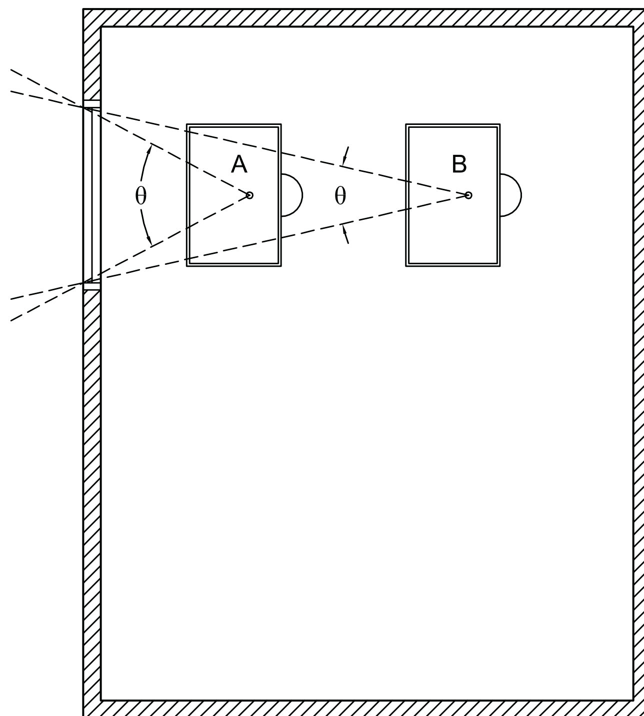


Figure 13.4c DISTANCE TO SOURCE: In this figure, both desks receive light from the same window. This time, desk B has a smaller exposure angle and gets less light because it is farther from the window.

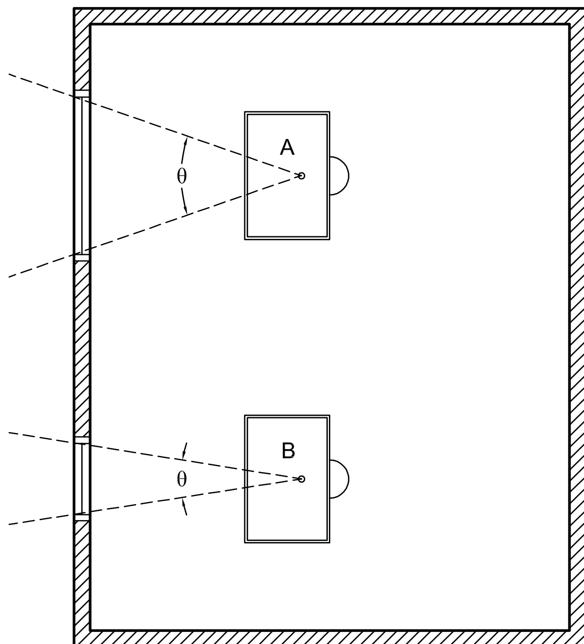


Figure 13.4b SOURCE SIZE: This figure shows a floor plan with two desks equally far from two windows of equal brightness. Desk B will receive less illumination because the smaller window produces a smaller exposure angle.

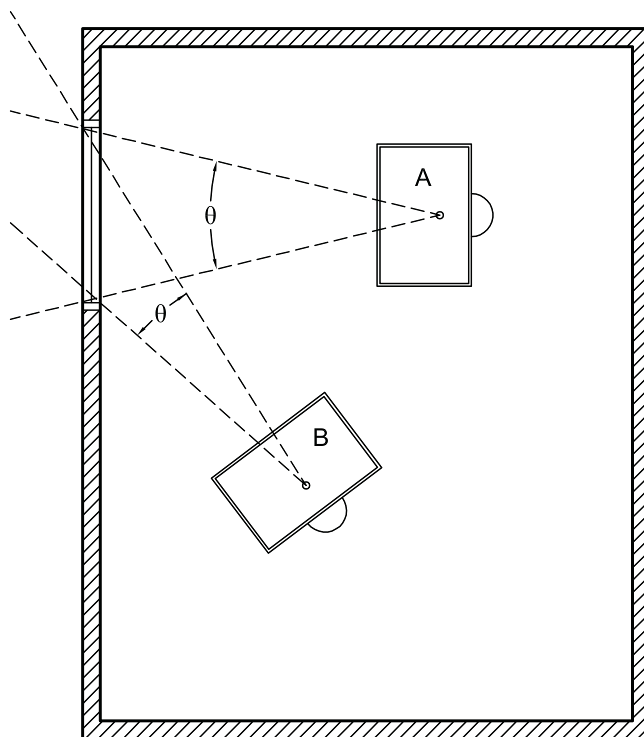


Figure 13.4d TILT OF SOURCE: In this figure, both desks are illuminated by the same window and they are equally far from the window. However, desk B now has a smaller exposure angle because the window is tilted relative to the desk.

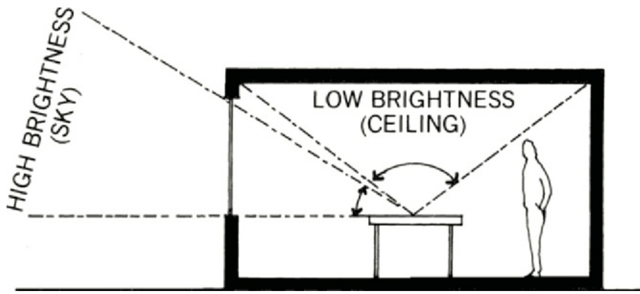


Figure 13.4e To determine the total illumination on the table, one must consider the brightness and exposure angle of each source in both plan and section. (After Moore, 1985.)

13.5 ILLUMINATION AND THE DAYLIGHT FACTOR

One of the best ways for the architect to determine both the quantity and the quality of a daylighting design is through the use of physical models. Although most daylighting model tests are conducted under the real sky, the actual measured illumination is of limited usefulness. Unless the model can be tested under the worst daylight conditions, the illumination inside the model will not indicate the lowest illumination level to be expected. Fortunately, it is not necessary to test the model under the worst conditions because of a concept called the **daylight factor** (DF).

The daylight factor is the ratio of the illumination indoors to outdoors on an overcast day (Fig. 13.5), which is an indication of the effectiveness of a design in bringing daylight indoors. For example:

A daylight factor (DF) of 5 percent means that on an overcast day when the illumination is 2000 footcandles outdoors, the illumination indoors will be 100 footcandles (2000 fc × 0.05 = 100 fc) or (20,000 × 0.05 = 1000 lux). Note that the daylighting factor is independent of the units used.

Although winter overcast skies are usually the worst design condition, the model can be tested under an overcast sky at any time of year or day. Table 13.5A presents typical daylight factors for different kinds of spaces. If the measured daylight factor is greater than that of Table 13.5A, there will be more than enough daylight for most of the year. A room with a DF above 5 will be well lit with little if any electric lighting needed for difficult visual tasks. In spaces designed with a DF of less than 4, supplementary task lights will be required for any difficult visual tasks that might occur there.

Since daylight decreases at a predictable rate as one moves north on the planet, it is possible to estimate the average indoor illumination from overcast skies by knowing the DF and the latitude. By multiplying the illumination for different latitudes given in Table 13.5B by the DF, it is possible to predict the average indoor illumination on an overcast day. If a design excludes direct sunlight, clear days will behave similarly to the overcast conditions described above. If direct sunlight is included, as it generally should be, then the model will have to be tested in sunlight to simulate the various sun angles throughout the year. The indoor illumination will then be much greater than the daylight factor would predict. Model testing will be explained later in this chapter.

Often, models are used to compare alternative designs. Since actual outdoor lighting varies greatly from hour to hour and day to day, footcandle (lux) measurements made at different times cannot be compared, but the daylight factor can. As the

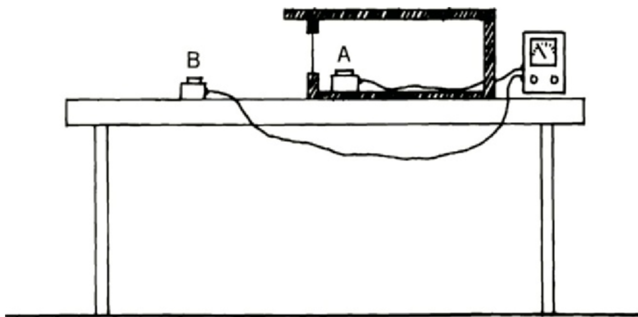


Figure 13.5 The daylight factor (DF) is determined by the ratio of indoor to outdoor illumination on an overcast day. DF = A/B.

Table 13.5A Typical Minimum Daylight Factors

Type of Space	Daylight Factor
Art studios, galleries	4–6
Factories, laboratories	3–5
Offices, classrooms, gymnasiums, kitchens	2
Lobbies, lounges, living rooms, churches	1
Corridors, bedrooms	0.5

Table 13.5B Average Illumination From Overcast Skies*

North Latitude (degrees)†	Illumination: Footcandles	Illumination: Lux
46	700	7000
42	750	7500
38	800	8000
34	850	8500
30	900	9000

*The illumination values are typical for overcast conditions, available about 85 percent of the day 8 A.M. to 4 P.M. For more detailed information, see *IESNA Lighting Handbook* (2000).
†See map of Fig. 5.6d.

outdoor illumination changes, the indoor illumination changes proportionally, and the daylight factor remains constant for any particular design for overcast skies.

13.6 LIGHT WITHOUT HEAT?

All light, whether electric or natural, is radiant energy that is eventually absorbed and turned into heat. In the winter this heat is an asset and in the summer a liability. Thus, we want to collect as much daylight as possible in the winter. As long as the collected light is quality light, there is no maximum in the underheated period because our pupils can shut out any excess. On the other hand, we want to collect just enough daylight in the summer so that the electric lights can be turned off.

At the same illumination level, daylight is cooler than electric lighting. Figure 13.6a shows the efficacy of various light sources. Note that light from the sky has the highest light-to-heat ratio. Although sunlight introduces more heat per unit of light than light from the sky, it is still better than any white, electric light source. For the same light level, incandescent lamps introduce about six times more heat than daylighting, and fluorescent lamps introduce about 1.5 times more heat than daylighting (90 lumens/watt for fluorescent lamps versus 120 lumens/watt for daylighting).

In the winter, there is no limit to the amount of sunlight that might be introduced as long as glare and excessive brightness ratios are controlled. After all, the daylighting indoors can never be brighter than the daylighting outdoors, for which the eyes evolved.

The seasonal problem of daylighting is most acute with skylights since horizontal openings receive much more sunlight in the summer than in the winter. South-facing vertical glazing is much better in this regard because it captures more sunlight in the winter than in the summer (Fig. 13.6b).

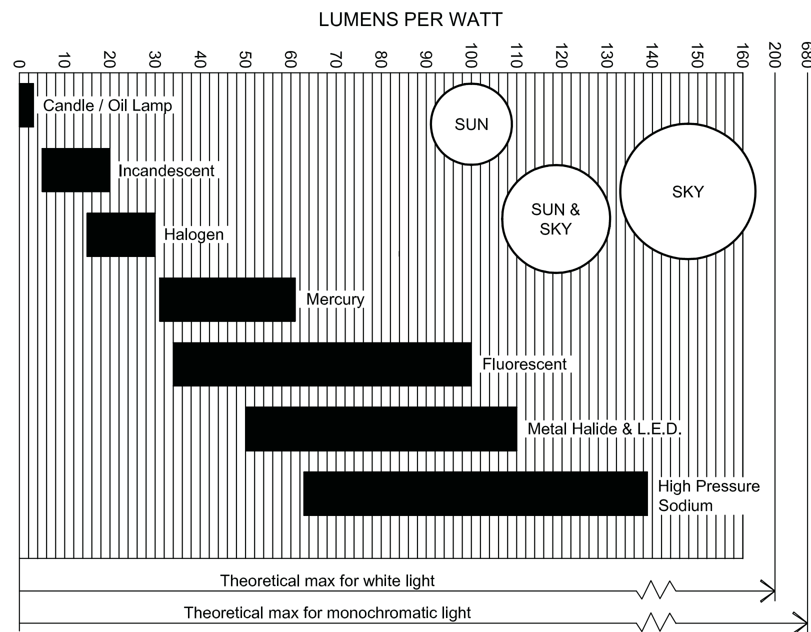


Figure 13.6a The efficacy (lumens/watt) of various light sources is compared.

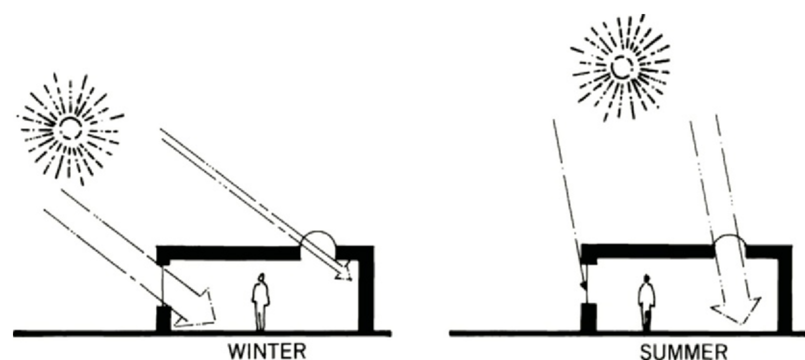


Figure 13.6b South-facing vertical glazing is more in phase with sunshine demand than is horizontal (skylight) glazing. Although the amount of daylight collected should be just adequate in the summer, there is almost no limit to the amount that is desirable in the winter in any building that has a heating system.

Rules for Daylighting Quantity

1. During the summer, introduce just enough daylight so that the electric lights can be turned off. The sunlight must be well distributed, and it must not raise the illumination levels much above the minimum that is required.
2. During the winter, introduce as much sunlight as possible in those buildings that need heating. There is no upper limit as long as it does not create glare or excessive brightness ratios.
3. Any building that does not need heating, such as an internally dominated building in a mild climate, should obey rule 1 in winter as well as in summer.
4. The efficacy of sunlight can be significantly increased over what is shown in Figure 13.6a if spectrally selective glazing is used in windows, as explained in the next section.

13.7 COOL DAYLIGHT

Because internally dominated buildings in warm climates need no heating, the coolest possible daylight should be collected. Cool daylight is possible because the heating effect of sunlight is not only a function of its amount but also of its spectral composition. Figure 13.7 (lower graph) illustrates the fact that about 50 percent of solar radiation is in the infrared part of the electromagnetic spectrum. This radiation enters a building through glazing just as visible light does, but it contributes nothing to lighting. Light reflected off clouds or from the blue sky has a smaller proportion of this infrared radiation. Since it has a higher light to heat ratio, the light from the sky has a higher efficacy (lumens per watt). Thus, it is a cooler daylight than sunlight.

Most materials have the same reflectance for short-wave infrared as for visible light. For example, the light reflected into a clerestory from a white roof has the same ratio of visible to short-wave infrared as the original sunlight did.

Glazing, however, can be made to either absorb or reflect some of the short-wave infrared. Tinted glazing is not a good choice for daylight because it blocks light as well as infrared radiation, it distorts the color of the daylight (and view), and it gets very hot by absorbing the light, thereby still heating the building unnecessarily. Reflective glazing is only a little better. Although it does not distort the color or heat the glass, it reflects light as much as the infrared radiation.

Heat-absorbing glass was developed to block more of this unwanted infrared radiation than light. Although it absorbs a slightly larger proportion of infrared than visible light, much of the absorbed radiation is reradiated inside and makes the glass uncomfortably hot. Its green tint also affects the color of the view. What is really needed for cool daylight is a selective glass that reflects the infrared but not the visible portion of daylight (see the upper graph of Fig. 13.7). There are now some new glazing materials commercially available that do this, and they are generally known as **spectrally selective low-e glazing**.

The ideal glazing type shown in Figure 13.7 (top) not only filters out the solar infrared but also the ultraviolet (UV) radiation that is especially bad for fading colored materials such as carpets, fabrics, artwork, paints, and wood. Special coatings or films on glass can filter out 100 percent of UV radiation. It is important to note, however, that all visible light (blue especially) causes fading. Valuable and delicate artifacts need to be shielded from both UV radiation and high-level light (i.e., above 15 footcandles [150 lux]).

Visible transmittance (VT or Tvis) is the factor that quantifies the amount of visible light that passes through glazing. It varies from 0.9 for very clear glass to less than 0.1 for highly reflective or tinted glass. For cool daylight, the VT should be high compared to the transmission of the solar infrared.

As mentioned in Section 9.20, the solar heat gain coefficient (SHGC) is a factor that quantifies the total solar radiation (visible, UV, and solar infrared) that passes through glazing.

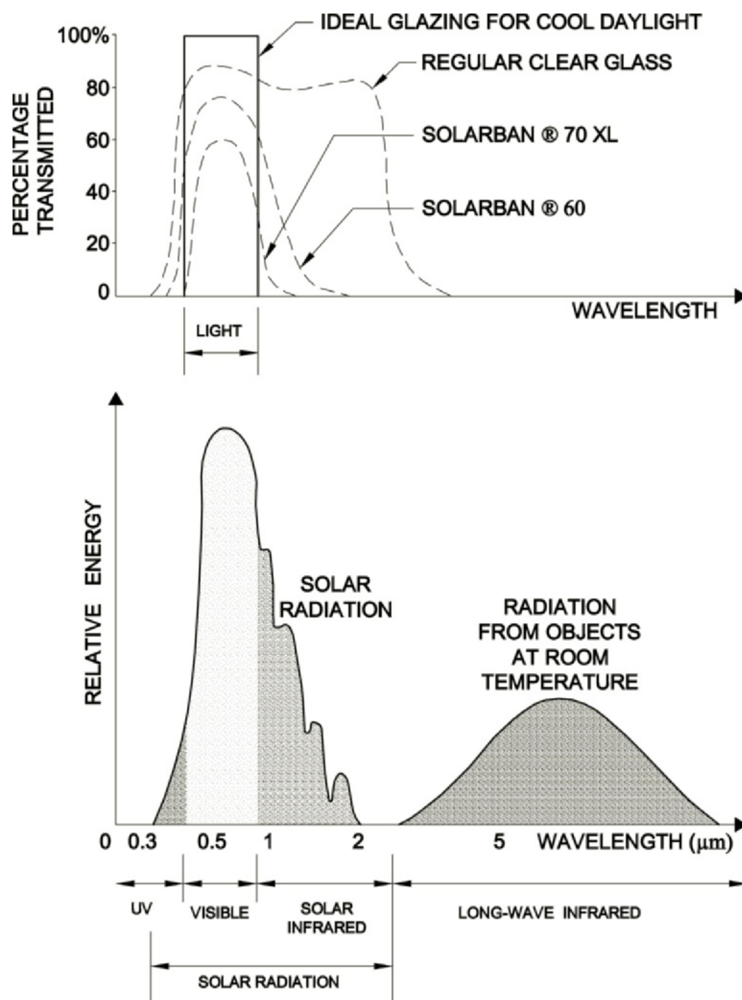


Figure 13.7 The ideal cool daylighting glazing would have a spectrally selective coating that allows the visible but not the infrared part of solar radiation to pass through. Compare this ideal behavior to that of regular glass. Two actual cool glazing products are shown to illustrate what is possible today.

SIDEBOX 13.7

$$TV = Tvis = \frac{\text{transmitted light}}{\text{incident light}}$$

$$\text{Light-to-solar-gain ratio} = \frac{\text{visible transmittance}}{\text{solar heat gain coefficient}}$$

or

$$LSG = \frac{VT}{SHGC}$$

Table 13.7 Light-to-Solar-Gain (LSG) Ratios for Various Glazing Systems

Glass Type (All Double-Glazed)	Visible Transmittance (VT)	Solar Heat Gain Coefficient (SHGC)	Light-to-Solar-Gain Ratio (LSG)
Clear	0.82	0.75	1.20
Bronze	0.62	0.60	1.03
Reflective	0.20	0.16	1.25
Spectrally selective	0.70	0.46	1.52

When one compares the VT to the SHGC, one can predict the coolness of the transmitted light. The ratio of the VT to the SHGC is called the **light-to-solar-gain** (LSG) ratio (see Sidebox 13.7). The higher the ratio, the cooler the light. See Table 13.7 for the LSG ratio for various types of glazing. Note that bronze glazing has a low LSG ratio because it blocks visible light more than solar heat which is certainly not desirable for cool daylighting purposes. On the other hand, spectrally selective glazing has a high LSG ratio because solar infrared is blocked much more than light.

Use spectrally selective low-e glazing when cool daylight is desired!

13.8 GOALS OF DAYLIGHTING

As stated above, the quantity goals of daylighting are to collect just enough light in the summer so that the electric lights can be turned off and to collect as much sunshine as possible in the winter to help meet the heating demand. Of course, for buildings that do not need heating because of their type and/or climate, the summer rule governs all year. The quality goals are the same as for electric lighting, and the main ones are: minimize glare, minimize veiling reflections, avoid excessive brightness ratios, and supply fairly even ambient illumination throughout a space.

Ordinary windows have trouble meeting these goals. The diagram in Figure 13.8a shows that typically there is too little light at the back of the room and more than enough right inside the window. Thus, the first goal is to get more light deeper into the building, both to raise the illumination level there and to reduce the illumination gradient across the room (Fig. 13.8b).

The second goal is to reduce or prevent the severe direct glare of unprotected windows and skylights. This glare is aggravated if the walls adjacent to the windows are not illuminated and, therefore, appear quite dark (Fig. 13.10f).

If a beam of sunlight creates a puddle of light over part of the work area, severe and unacceptable brightness ratios will exist. Thus, the third goal is to prevent excessive brightness ratios, especially those caused by direct sunlight on or near the task (Fig. 13.8c).

Although the low-angle light from windows is usually not a source of veiling reflections, on horizontal tasks the light from overhead openings can be (Fig. 13.8d). The exception is veiling reflections on computer monitors from windows. Thus, the fourth goal is to prevent or minimize veiling reflections from skylights, clerestory windows, and high windows.

In most situations, lighting should not be too directional because of the glare and dark shadows that result. The fifth goal, therefore, is to diffuse the light by means of multiple reflections off the ceiling and walls.

In areas where there are no critical visual tasks, the drama and excitement of direct sunlight can be a positive design element. Therefore,

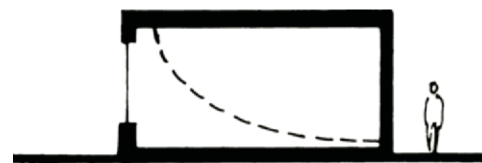


Figure 13.8a The light from windows creates an excessive illumination gradient across the room (too dark near the back wall compared to the area near the window).

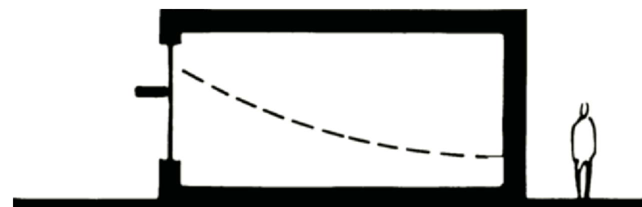


Figure 13.8b One goal of daylighting design is to create a more acceptable illumination gradient.

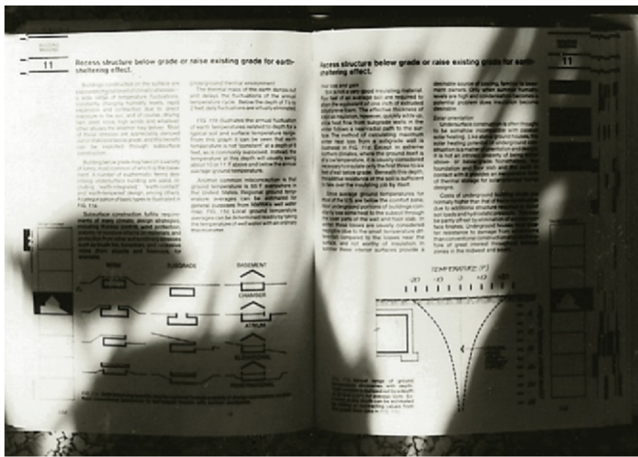


Figure 13.8c Excessive brightness ratios can result from puddles of sunlight, especially when on or near the task.

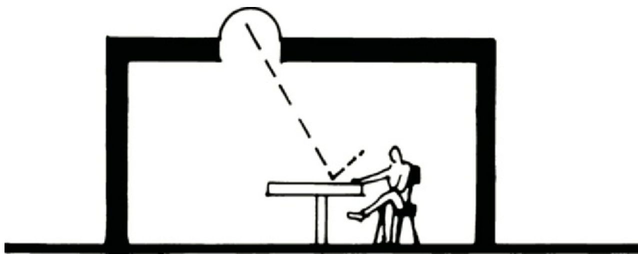


Figure 13.8d Veiling reflections are a common problem from any overhead lighting.

the sixth goal, which is limited to those spaces in which there are few if any critical visual tasks, is to use the full aesthetic potential of daylighting and sunlight. In all spaces, however, the dynamic nature of daylight should be seen as an asset rather than a liability. The ever-changing nature of daylight needs only to be limited—not eliminated.

Unlike electric lighting, daylighting cannot just be added to the building. Daylighting design is part of the fundamental building design from the first line drawn, and the best daylighting results from an integrated design process where the interaction of design decisions is fully appreciated. The most critical decisions for daylight are made in creating the form and setting the orientation of a building. Next come window size, location, and treatment. Also important are indoor wall color and the design of partitions because they stop the spread of light unless they are made of glass.

The remainder of this chapter discusses techniques and strategies for achieving the above-mentioned goals.

13.9 BASIC DAYLIGHTING STRATEGIES

Although daylighting is primarily a second-tier strategy (Fig. 13.9a), it is important to utilize as many of the tier-one strategies listed below as possible to enhance and prepare for the daylighting design.

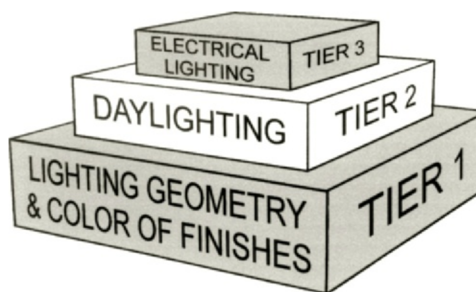


Figure 13.9a The best and most sustainable lighting is achieved by the three-tier design approach, and this chapter covers primarily tier two. However, many tier-one strategies are critical to make daylighting succeed.

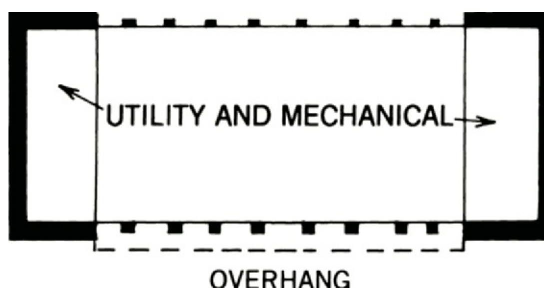


Figure 13.9b The ideal plan for daylighting, as well as general solar control, has all windows facing north and south.

Basic Daylighting Guidelines

1. *Orientation*. Because of the usefulness of direct sunlight, the south orientation is usually best for daylighting. The south side of a building gets sunlight most consistently throughout the day and the year. This extra sunlight is especially welcome in the winter, when its heating effect is often desirable. Sun-control devices are also much more effective on the south than any other orientation.

   The second-best orientation for daylighting is north because of the constancy of the light. Although the quantity of north light is rather low, the quality is high if a cool white light is acceptable (see Colorplate 16). There is also little problem with glare from the direct sun. In very hot climates, the north orientation might even be preferable to the south orientation.

   The worst orientations are east and west. Not only do these orientations receive sunlight for only half of each day, but the sunlight is at a maximum during summer instead of winter. The worst problem, however, is that the east or west sun is low in the sky and, therefore, creates

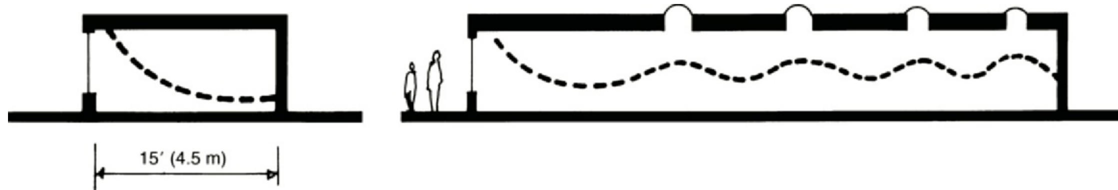


Figure 13.9c While daylighting from windows is limited to the area about 15 ft (4.5 m) from the outside walls, roof openings can yield fairly uniform lighting over unlimited areas.

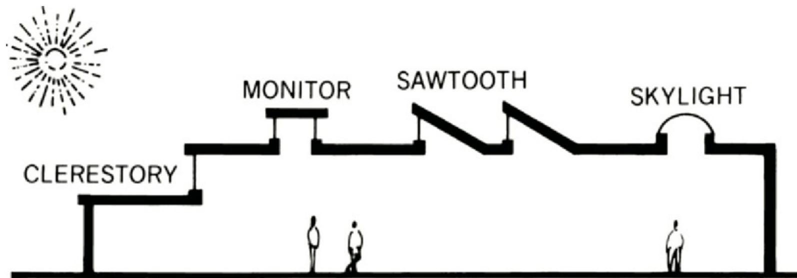


Figure 13.9d The various possibilities for overhead openings for daylighting are shown.

very difficult glare and shading problems. Figure 13.9b illustrates an ideal floor plan in regard to building orientation.

Rules for Orientation

1. (a) For daylighting when winter heat is desirable, use south-facing glazing.
   (b) For daylighting when winter heat is not desirable, use north-facing glazing.
   (c) To prevent summer overheating and severe glare, avoid east and west glazing.
2. *Lighting through the roof*. Except for the use of light wells, only one story or the top floor of multistory buildings can use overhead openings. When applicable, horizontal openings (skylights) offer two important advantages. First, they allow fairly uniform illumination over very large interior areas, while daylighting from windows is limited to about a 15 ft (4.5 m) perimeter zone (Fig. 13.9c). Second, horizontal openings also receive much more light than vertical openings. Unfortunately, there are also two important problems associated with skylights. The intensity of light is greater in the summer than in the winter—just the opposite of what we want. It is also difficult to shade horizontal glazing. For these two reasons, it is usually more appropriate to use vertical glazing on the roof in the form of clerestory windows, monitors, or sawtooth arrangements (Fig. 13.9d).
3. *Form*. The form of the building determines how many windows can be placed on each orientation, how many skylights or clerestories can be placed on the roof, and how much of the floor area will have access to daylighting. Generally, in multistory buildings a 15 ft (4.5 m) perimeter zone can be fully daylit and another 15 ft (4.5 m) beyond that can be partially daylit by windows. All three floor plans in Figure 13.9e have the same area (10,000 ft^2 [900 m^2]). In the square plan, 16 percent is not daylit at all, and another 33 percent can be only partially daylit. The rectangular plan can eliminate the core area that receives no daylight, but it still has a large area that is only partially daylit, while the atrium scheme is able to have all of its area daylit. Of course, the actual percentage of core versus perimeter zones depends on the actual area of a building. Larger buildings will have larger cores and less surface area. The modern atrium is typically an enclosed space whose temperature is maintained close to the indoor conditions. Buildings with atriums are, therefore, compact from a thermal point of view and yet have a large exposure to daylight. The amount of light available at the base of the atrium depends on a number of factors: the translucency of the atrium roof, the reflectance of atrium walls, and the geometry of the space (depth versus width), as shown in Figure 13.9f. Physical models are the best way to determine the amount of daylight that can be expected at the bottom of an atrium. When atriums get too small to be useful spaces, they are known instead as light wells. Atriums can be illuminated by skylights, clerestories, or window walls (Fig. 13.9g). The advantage of each approach will be explained below in the discussion of windows, skylights, and clerestories.
4. *Space planning*. Open space planning is very advantageous for borrowed light, which brings light farther into the interior. Glass partitions can furnish acoustical privacy without blocking the light. When visual privacy is also

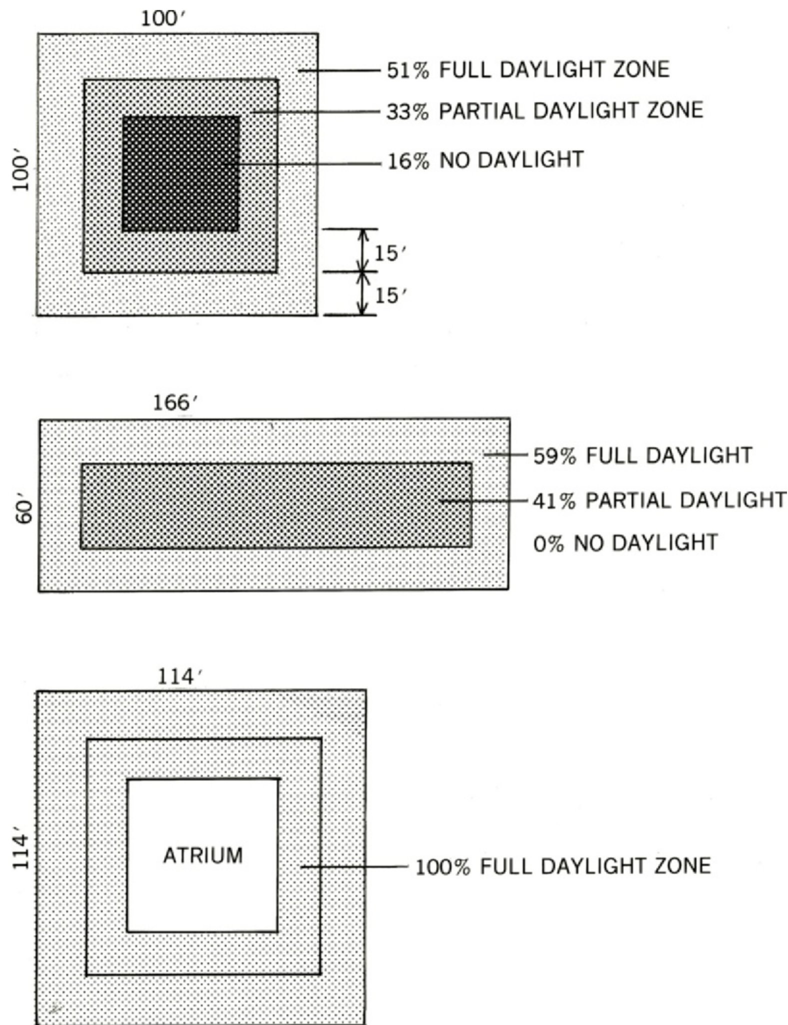


Figure 13.9e These alternative plans of a multistory office building illustrate the effect of massing on the availability of daylight.

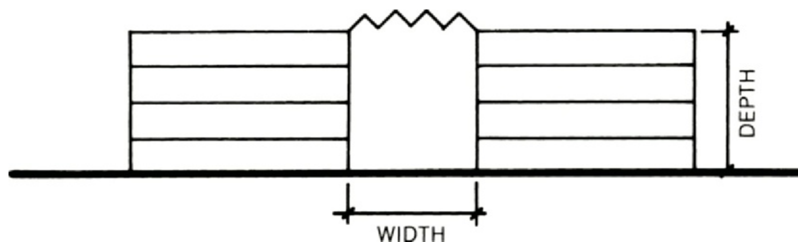


Figure 13.9f It is not the actual depth or width but their ratio that determines how much daylight will be available at the base of an atrium.

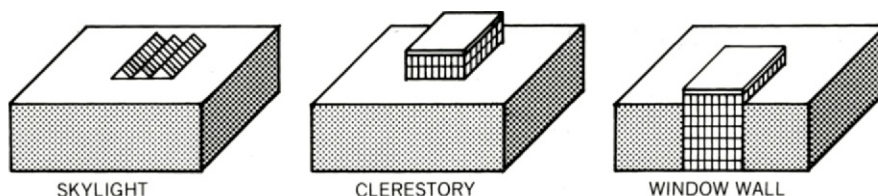


Figure 13.9g Generic types of daylit atriums are shown.

needed, venetian blinds or translucent materials could be used. Alternatively, the partitions could have glass above eye level only (Fig. 13.9h). Sometimes the partitions must be fire rated, and any partition facing an egress corridor must be fire rated. Fortunately, new fire-resistant glazing systems allow a two-hour rating even with unlimited glazing areas.

5. *Color*. Use light colors both indoors and outdoors to reflect more light into the building and farther into the interior. Light-colored roofs can greatly increase the light that clerestories collect. White or light-colored exterior walls also increase daylighting for windows adjacent to projecting building wings as well as for windows in neighboring buildings. Light-colored facades are especially important in urban areas to increase the availability of daylighting at the lower floors and sidewalks. Light-colored interiors will not only reflect light farther into the building but also diffuse it to reduce dark shadows, glare, and excessive brightness ratios. The ceiling should have the highest reflectance factor possible. The floor and small pieces of furniture are the least critical reflectors and, therefore, might have fairly low reflectance factors (dark finishes). The descending order of importance for reflecting surfaces is: ceiling, back wall, side walls, floor, and small pieces of furniture (Fig. 13.9i). Not shown but most important for glare control is the wall around the window.
6. *View and daylighting*. Use separate openings for view and daylighting. Use high windows, clerestories, or skylights for excellent daylighting, and use low windows at eye level for view. High glazing should be clear or spectrally selective to maximize the daylight collected. The view glazing is more flexible and can be designed to

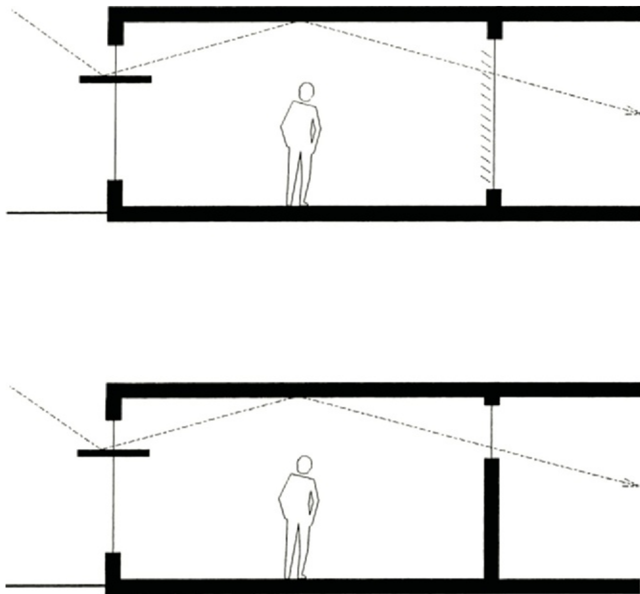


Figure 13.9h Full- or partial-height glass partitions can enable "borrowed" light to enter farther into interior spaces.

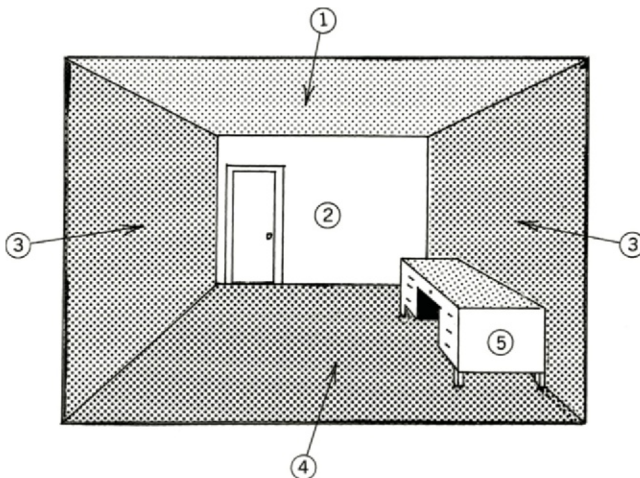


Figure 13.9i For good distribution and penetration of light, the order of importance for high reflectance finishes is shown (e.g., surface 1 should have the highest reflectance factor).

transmit less light in order to control heat gain and glare.

For daylighting, south is the best orientation, north is the second-best, and east and west are poor!

13.10 BASIC WINDOW STRATEGIES

To understand window daylighting strategies, it is worthwhile to first examine the lighting from an ordinary window. As mentioned earlier, the illumination is greatest just inside the window and rapidly drops off to inadequate levels for most visual tasks (Fig. 13.10a left). The view of the sky is often a source of direct glare, and direct sunlight entering the window creates excessive brightness ratios (puddles of sunlight as well as overheating during the summer). To overcome these negative characteristics of ordinary windows, designers should keep in mind the following strategies:

Guidelines

1. Windows should be high on the wall, widely distributed, and of optimum area. Daylight penetration into a space will increase with the mounting height of the window (Fig. 13.10a right). The useful depth of a daylit space is limited to about 1½ times the height of the top of the window. Thus, whenever possible, ceiling heights should be increased so that windows can be mounted higher.

   Daylight will be more uniformly distributed in a space if windows are horizontal rather than vertical and if they are spread out rather than concentrated (Fig. 13.10b). Architects such as Le Corbusier often used high ribbon windows for these reasons (Fig. 13.10c).

   Window area as a percentage of floor area should generally not exceed 20 percent because of summer overheating and winter heat losses. By means of reflectors, small-window areas can collect large amounts of daylight. However, in very cloudy or cold climates, movable shading systems and high-performance windows can increase the optimum window area.
2. If possible, place windows on more than one wall. Whenever possible, avoid unilateral lighting (windows on one wall only), and use bilateral lighting (windows on two walls) for much better light distribution and reduced glare (Fig. 13.10d). Windows on adjacent walls are especially effective in reducing glare. The windows on each wall illuminate the adjacent walls and, therefore, reduce the contrast between each window and its surrounding wall.
3. Place windows adjacent to interior walls. Here, the interior walls adjacent to windows act as low-brightness reflectors to reduce the overly strong directionality of daylight (Fig. 13.10e). The glare of the window is also reduced because of the reduced brightness ratio between the window and its surrounding wall due to reflections back from the side wall (Fig. 13.10f).

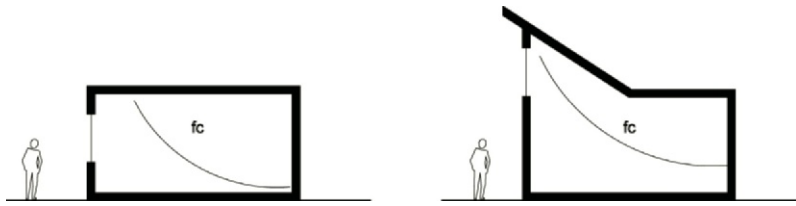


Figure 13.10a Daylight penetration increases with window height.



Figure 13.10b These plans, with contours of equal illumination, illustrate how light distribution is improved by admitting daylight from more than one point. The plan on the right is also better because the walls adjacent to the windows will be brighter, thereby reducing glare (also see Fig. 13.10f).



Figure 13.10c Strip or ribbon windows, as seen here in the Maison La Roche by Le Corbusier, admit uniform light, which is further improved by placing the windows high on the wall. Note that photographic film exaggerates brightness ratios. (Photograph by William Gwin.)

4. Splay walls to reduce the contrast between windows and walls. Windows create less glare when the adjacent walls are not dark in comparison to the window. Splayed or rounded edges create a transition of brightness that is more comfortable to the eye (Fig. 13.10g).
5. Filter daylight. Sunlight can be filtered and softened by trees or by such devices as trellises and screens (Fig. 13.10h). Translucent glazing or very light drapes, however, can make the direct-glare problem much worse. Although they diffuse direct sunlight, they often become excessively bright sources of light in the process (Fig 13.10i).
6. Shade windows from excess sunlight in summer. Ideally, only a small amount of sunlight should be admitted through the windows in the summer and a maximum amount in the winter. At all times, however, the light should be diffused by reflecting it off the ceiling. Overhangs on south windows can provide this seasonal control. They can also eliminate puddles of sunlight, reduce glare, and even out the light gradient across the room. If a large, solid horizontal overhang is used, its underside should be painted white to reflect useful ground light

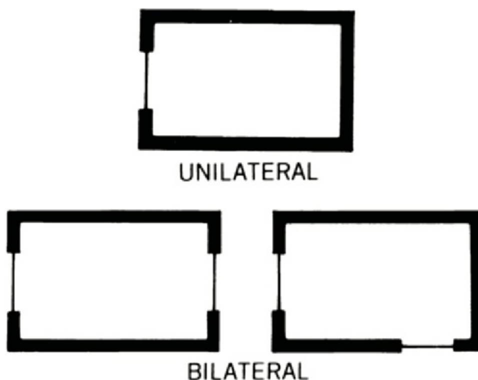


Figure 13.10d Bilateral lighting is usually preferable to unilateral lighting (plan view).

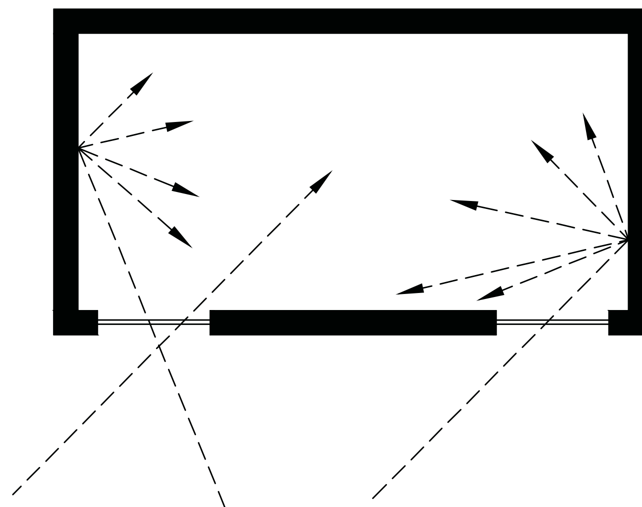


Figure 13.10e Light distribution and quality are improved by the reflection off sidewalls.

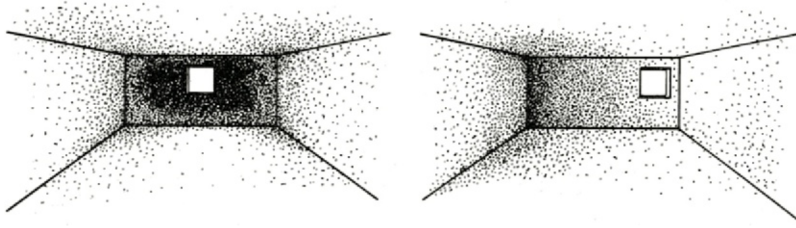


Figure 13.10f The glare from a window next to a sidewall is less severe than that from a window in the middle of a room, because of the light reflected off the side wall.

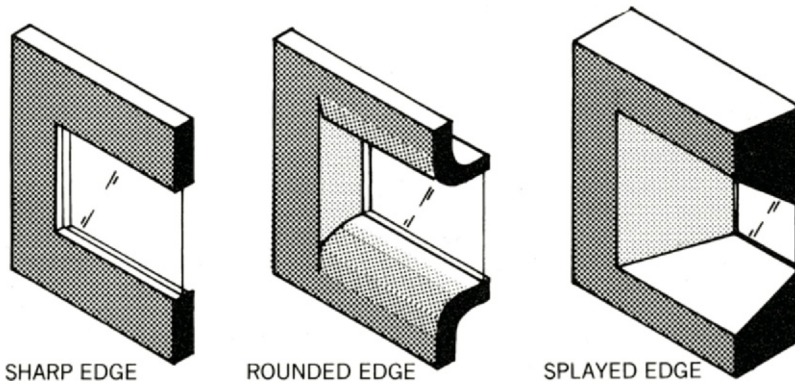


Figure 13.10g The excessive contrast between a window and a wall can be reduced by splaying or rounding the indoor edges. (After M. D. Egan, *Concepts in Architectural Lighting*.)



Figure 13.10h Trees, supported on a grid of wires, filter the light before it enters the Kimbell Art Museum, Fort Worth, Texas. Louis I. Kahn, architect.

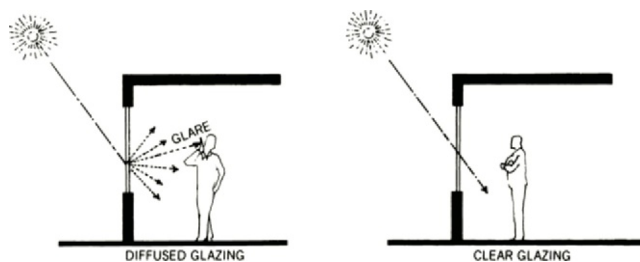


Figure 13.10i Translucent glazing can be a major source of glare because some of the sunlight is directed into the eyes of the observer. However, translucent glazing can be beneficial if it is out of the field of view (i.e. very high windows, clerestories, or skylights).

(Fig. 13.10j). A light-colored overhang, especially with louvers, will also reduce the brightness ratio between itself and the sky.

Louvers in a vertical or horizontal plane painted a light color are beneficial because they block direct sunlight yet reflect diffused sunlight (Fig. 13.10k). A vertical panel in front of a window can block direct sunlight while reflecting diffused skylight into the window (Fig. 13.10l).

Chapter 9 contains an extensive description of shading devices. Physical models can be used to determine how well these and other devices can admit quality daylight while shading direct sunlight. Of course, in certain spaces, such as lobbies, lounges, and living rooms, where visual tasks are not critical, some direct sunlight can be welcome for its visual and psychological benefits, especially in winter.

7. Use movable shades. A dynamic environment calls for a dynamic response. Variations in daylighting are especially pronounced on the east and west exposures, which receive diffused light for half a day and direct sunshine for the other half. Movable shades, venetian blinds, or curtains can respond to these extreme conditions. To reduce heat gain, the interior shading devices must be highly reflective.

   Although indoor shading is simpler, outdoor shading is much more effective. Movable outdoor venetian blinds are very popular in Germany and Austria. They are sturdy enough to resist wind, snow, and ice, and they are usually made of reflective aluminum to either reflect the sun away or to the ceiling indoors (see Fig. 9.4n).

   The Bateson Building uses exterior roller shades for the same purpose (Fig. 13.10m). The fabric is translucent so that

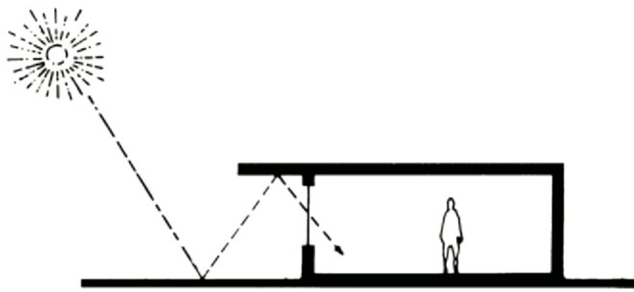


Figure 13.10j Large, horizontal overhangs block too much light unless both the ground and the underside of the overhang have high reflectance values.

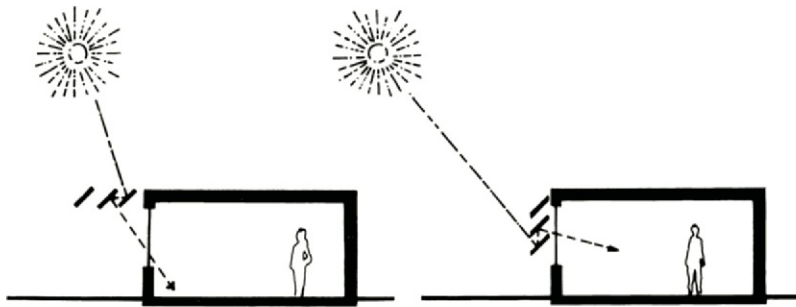


Figure 13.10k Light-colored louvers block direct sunlight but allow some diffused light to enter the windows.

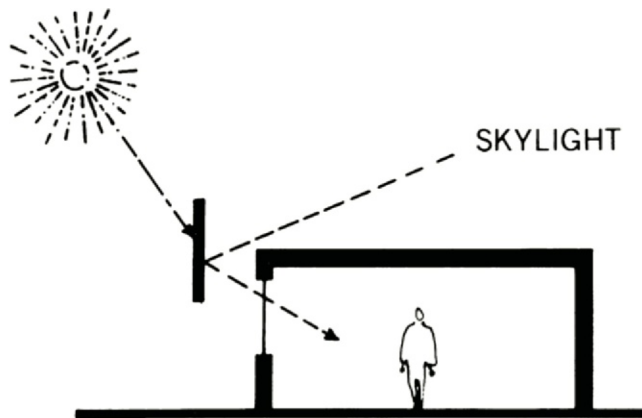


Figure 13.10l A vertical panel can block direct sunlight while it reflects diffuse skylight.

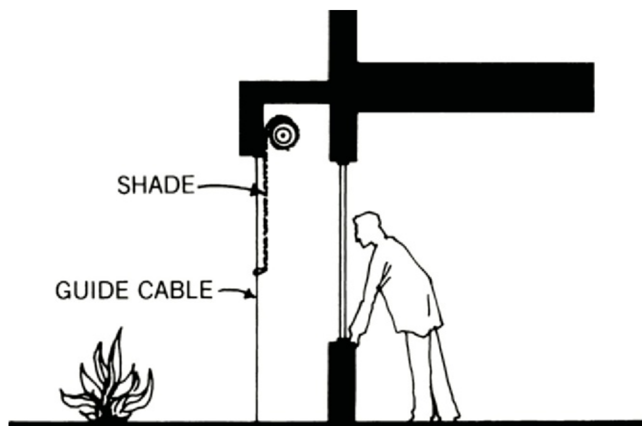


Figure 13.10m On the east and west facades, the Bateson Building in Sacramento, California, uses exterior translucent roller shades that automatically respond to sun and wind conditions.

some light still enters even when most of the sun is blocked.

In almost all of the strategies mentioned so far, most of the light enters the windows from above or horizontally. It would be much better if the light entered from below to illuminate the ceiling, as the next section will explain.

13.11 ADVANCED WINDOW STRATEGIES

The challenges of getting daylight from windows farther into the building while still maintaining the quality of the lighting can best be met by reflecting daylight off the ceiling. Walkways, roads, and light-colored patios can reflect a significant amount of light to the ceiling in one-story buildings (Fig. 13.11a). In multistory buildings, parts of the structure can be used to reflect light indoors. Deep windowsills can be quite effective but are a potential source of glare on the south, east, and west facades. However, they are a good idea on north windows to increase the collection of low-brightness diffuse light from the sky (Fig. 13.11b). Light shelves prevent glare when placed just above eye level (Fig. 13.11c). If glazing is used below the light shelf, it will be mainly for view. The light shelf acts as an overhang for this lower glazing to prevent direct sunlight from entering and creating puddles of sunlight. The overhang also reduces glare by blocking the view of the bright sky in the lower window. Glare from the upper window can be controlled by louvers (Fig. 13.11c) or by an additional light shelf on the inside (Fig. 13.11d). Light shelves will not only improve the quality of the daylighting, but also increase the depth of the daylighting zone (Fig. 13.11e).

Light shelves must be much longer on east and west windows than on south windows, and they are not

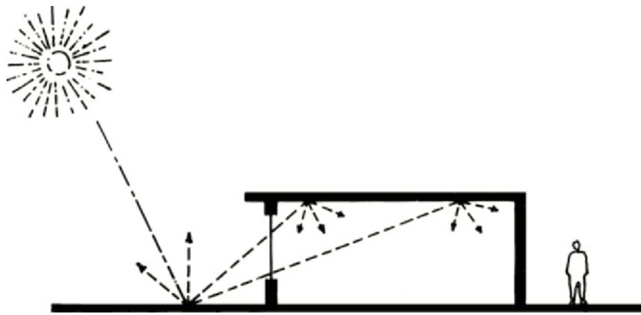


Figure 13.11a Light-colored pavement or gravel can reflect light deep into the interior.

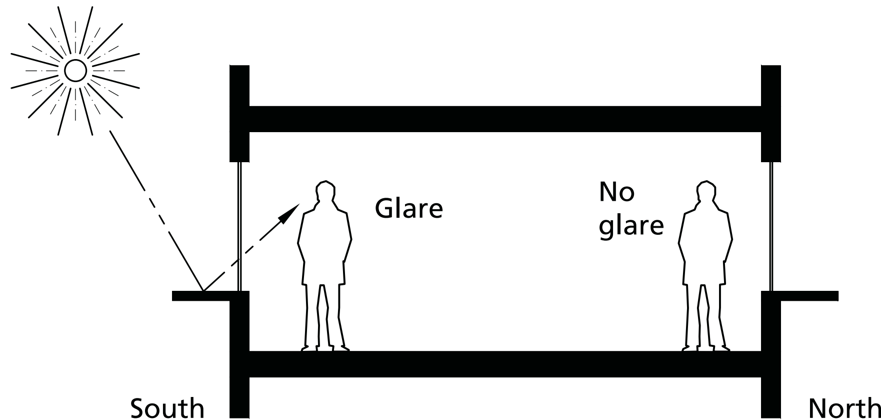


Figure 13.11b Wide windowsills can be used as light reflectors to send light deep into the interior, but they can be a source of glare except on north windows.

needed at all on north windows. Thus, every orientation needs a different window design (Fig. 13.11f). Since east and west windows are exposed to the low summer sun, they need extra-deep light shelves, louvers, ribbon windows, and an occasional view window.

The use of light shelves only on the indoor side of windows is much less useful because less light is collected and the view windows are not shaded (Fig. 13.11g).

The Ventura Coastal Corporation's administration building is an excellent example of a building using light shelves (Fig. 13.11h). A sloped ceiling allows the windows to be large and high for extensive daylight penetration and the necessary mechanical equipment to be concentrated near the center of the building, where more room exists above the ceiling (Fig. 13.11i). North windows are also very large and high because of the sloping ceiling. In this very mild climate, the north-facing

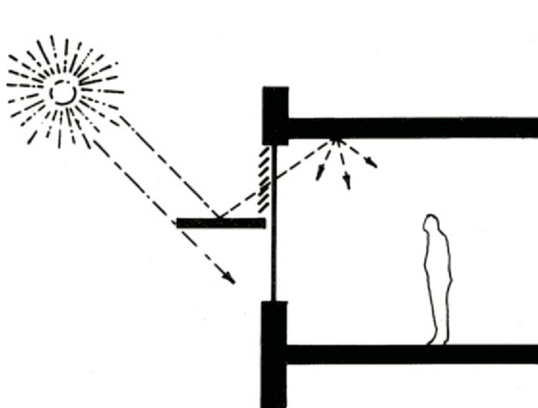


Figure 13.11c Light shelves are placed above eye level to prevent glare from the top of the shelf. In this position, they also act as overhangs for the view windows underneath. Louvers or an additional interior light shelf can be used to prevent glare from the clear glazing above the light shelf.

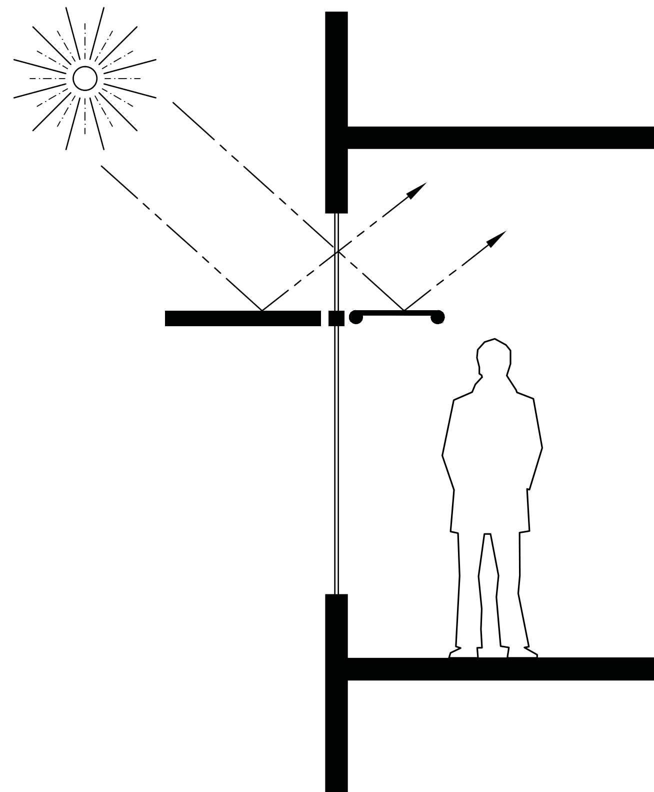


Figure 13.11d A second light shelf on the interior is more effective in collecting daylight and throwing it farther into a room than using louvers to control the sunlight entering through the upper daylight glazing. Unlike the outdoor light shelf, the indoor light shelf can be very delicate (e.g., a white film or fabric stretched on a light metal frame.

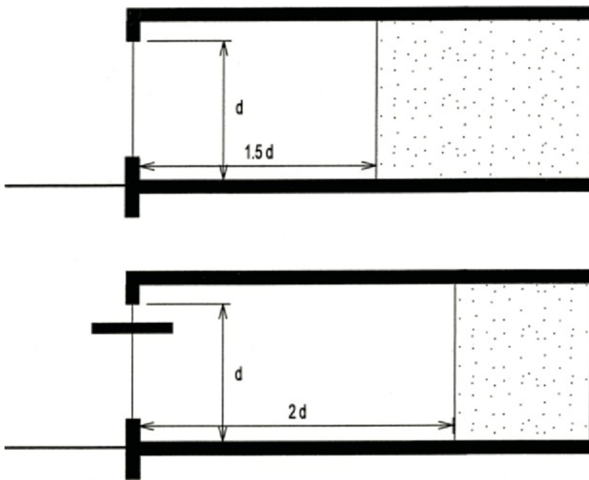
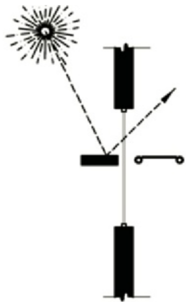
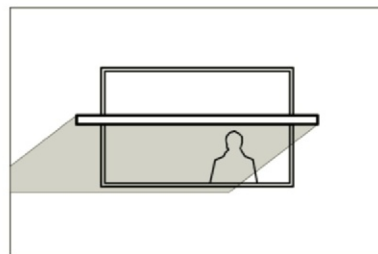
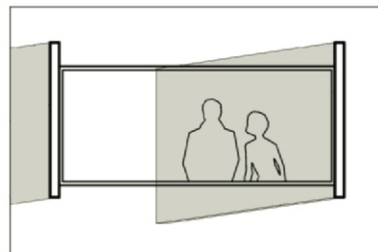


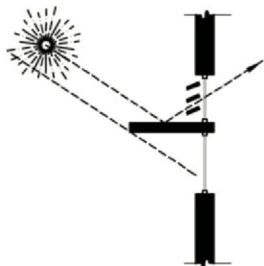
Figure 13.11e A rule of thumb for daylight penetration is 1½ times the height of a standard window and 2 times the height of a window with a light shelf for south-facing windows under direct sunlight. (After *Tips for Daylighting*, by Jennifer O'Connor, © Regents of the University of California, 1997.)











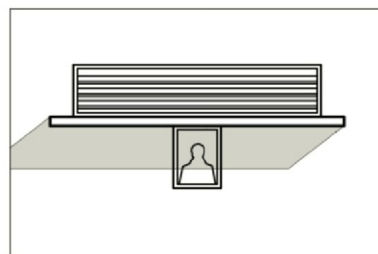


Figure 13.11f Each orientation should have a different window design. Light shelves work very well on south windows, but not on north windows, where they block more daylight than they collect. North windows, however, need fins to shade the early morning and late afternoon sun. On the difficult east and west facades, use short and wide daylight windows with deep light shelves. View windows should be few and small.

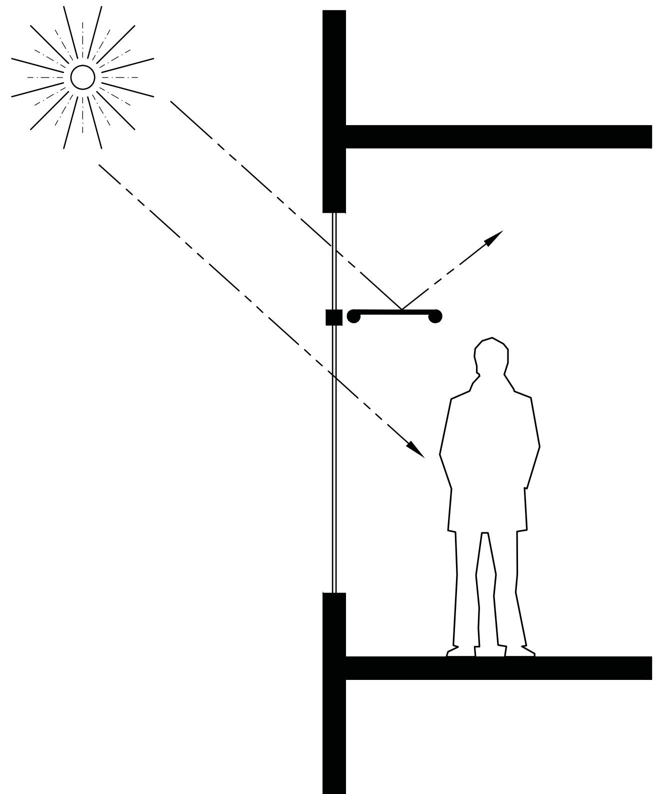


Figure 13.11g Although temptingly convenient, having light shelves only on the indoor side of windows misses the opportunity for the light shelves to also shade the view windows. It is best to have them both outdoors and indoors.



Figure 13.11h The Ventura Coastal Corporation's administration building in Ventura, California, uses light shelves to daylight the building. Architect: Scott Ellinwood. (Courtesy of and © Mike Urbanek, 1211 Maricopa Highway, Ojai, CA 93023.)

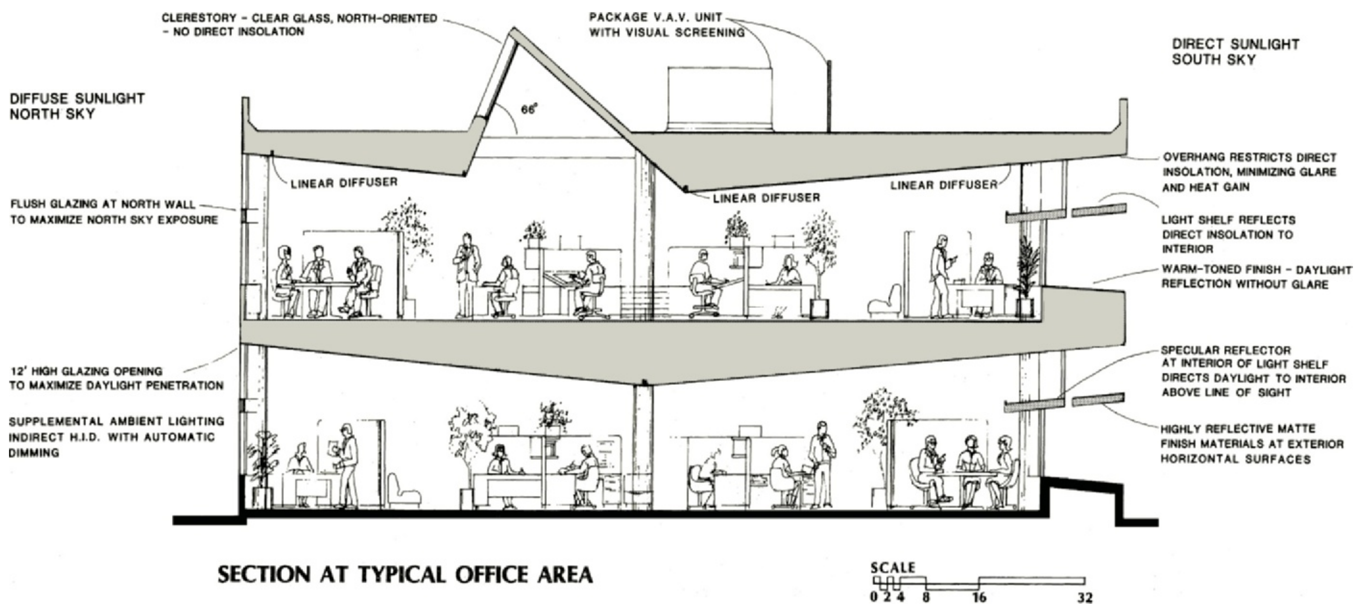


Figure 13.11i Light shelves, sloped ceilings, clerestories, north-facing windows, and open planning all help to illuminate the Ventura Coastal Corporation's administration building during the day. (Courtesy of and © Mike Urbanek, 1211 Maricopa Highway, Ojai, CA 93023.)

clerestory brings light into the center of the building so that the illumination from daylighting is more evenly distributed.

Light shelves have become very popular even on a very large and high building such as the twenty-story Home Depot headquarters in Atlanta (Fig. 13.11j). Light shelves are also found on small and lightweight buildings such as the Florida Solar Energy Center, which makes its very slender light shelves hurricane-proof with cable stays (Fig. 13.11k).

One of the most effective and oldest strategies for reflecting light onto the ceiling is the use of venetian blinds. Outdoor venetian blinds are more effective in stopping heat gain than interior blinds, and they add a rich texture to the facade. The venetian blind's main drawback, dirt accumulation, can largely be avoided by sandwiching the blind between two layers of glass (Fig. 13.11l left). Miniature slats reduce the annoying figure/background effect described in Figure 12.6h. Dynamic systems such as venetian blinds are much more effective than static systems because they can better respond to the varying conditions of daylight and sunlight.



Figure 13.11j Light shelves do not have to protrude from the facade, as seen here in the twenty-story Home Depot headquarters in Atlanta, Georgia.



Figure 13.11k Thin metal light shelves are supported by cables. The top of the shelf is a high-reflectance white, while the rest is painted a bright yellow. The photo was taken before the indoor light shelves were installed.

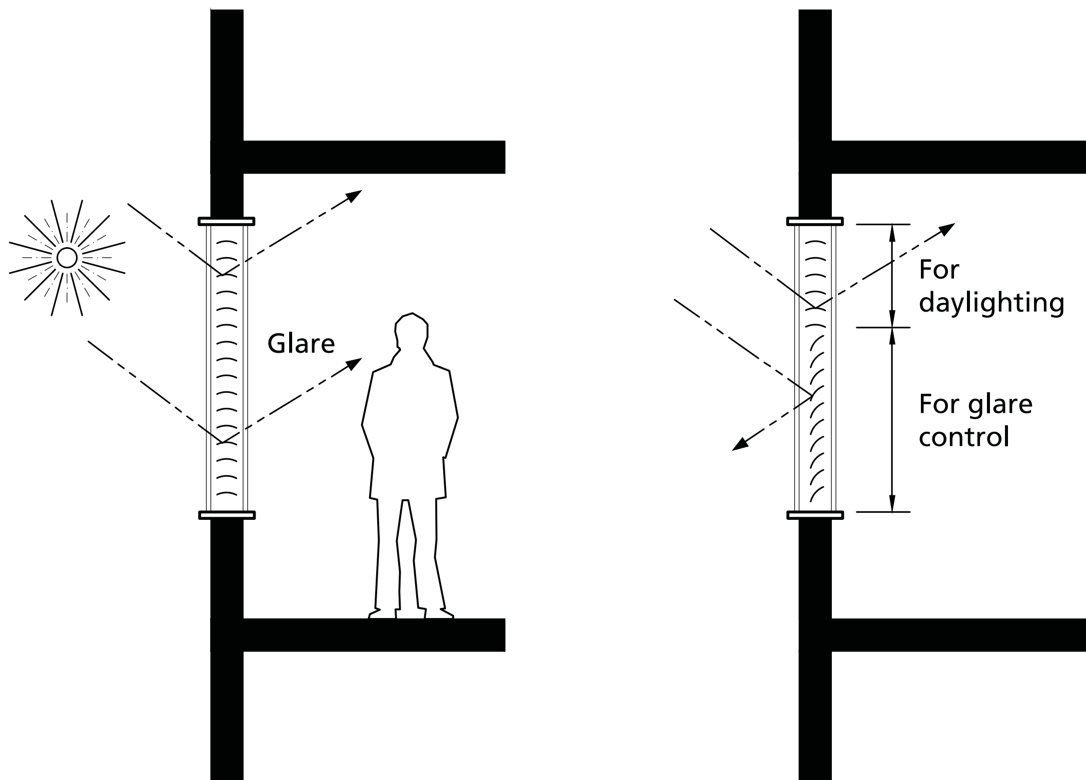


Figure 13.11l To prevent dirt accumulation, venetian blinds can be sandwiched between two layers of glass, but they are most effective if placed on the exterior of the glazing. For daylighting purposes, they should come in pairs: the top one for daylighting and the bottom one for glare control. They are especially appropriate on east and west facades because they can block the low sun.

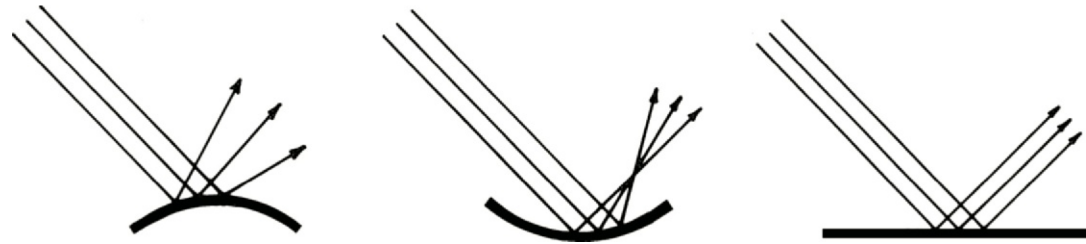


Figure 13.11m Both concave and convex specular reflectors can be used to distribute daylight over a wide area of the ceiling.

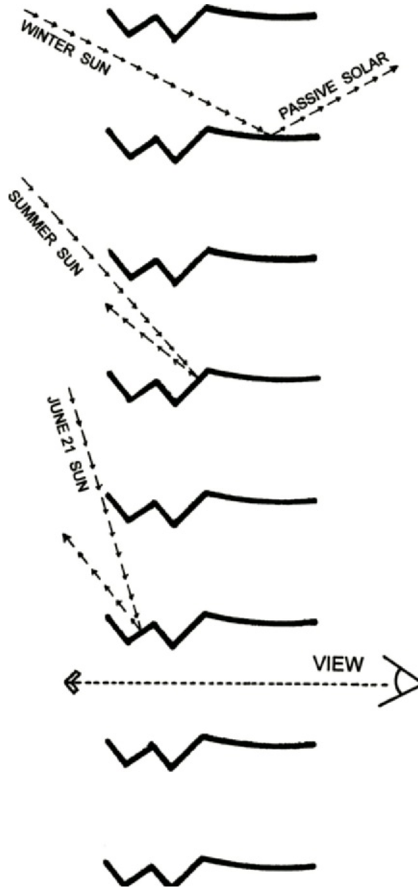


Figure 13.11n This venetian blind was designed to reject the summer sun and collect the winter sun while remaining essentially horizontal in order to maximize the view.

Instead of placing venetian blinds indoors or inside a sealed double-glazing unit, they can also be placed in a **double skin** system (also called **smart facades** or **climate facades**) where the glazing is about 12 inches (0.3 m) apart. The double skin system both protects the venetian blind and allows for natural ventilation, even in skyscrapers like the fifty-six-story Commerzbank in Frankfurt, Germany (see Figs. 10.10a and 10.10b).

No matter where the venetian blind is located, it should come in a set of two for daylighting purposes. As Figure 13.11l (right) shows, the upper venetian blind is set for reflecting daylight onto the ceiling while the lower one is adjusted as needed to control glare.

In all cases, the ceiling should be a diffusing reflector such as white paint, but the devices reflecting light onto the ceiling could have a specular finish in order to maximize the depth of sunlight penetration. Figures like 13.11b were drawn for clarity as if the reflectors had a specular finish. Unless they are specifically labeled, assume that the reflectors shown in the diagrams are diffusing in nature. A disadvantage of specular reflectors is that they often cast excessively bright patches of sunlight on the ceiling. Curved specular reflectors minimize this problem by spreading the sunlight over a large part of the ceiling (Fig. 13.11m). Matte reflectors, on the other hand, create a very even distribution of light and are much less sensitive to sun angles. Model studies are a good way to determine whether specular or diffuse reflectors should be used.

When venetian blinds are rotated to block the summer sun or to maximize the winter sun, they often block the view. To correct this problem and eliminate the need for seasonal adjustments, a new type of venetian blind has been developed. The special shape of the louvers automatically blocks the summer sun and collects the winter sun with minimum obstruction of the view (Fig. 13.11n).

Another product with specially shaped louvers is designed to act like a light shelf without any projection on either the exterior or interior. The Lightlouver is placed above the view window, where it reflects sunlight to the ceiling irrespective of incoming sun angle.

Rules for Advanced Daylighting from Windows

1. Use light shelves on the south facade.
2. Use a large projecting outdoor windowsill and small fins on north windows.
3. Use a dynamic system like outdoor venetian blinds on the east and west facades.
4. Use a backup system like venetian blinds on all interior facades for blocking low sun angles, glare control, and room darkening.

13.12 WINDOW GLAZING MATERIALS

Choosing the right glazing material is critical to a successful daylighting design. Transparent glazing comes in a variety of types: clear, tinted, heat-absorbing, reflective, and spectrally selective.

The tinted, heat-absorbing, and reflective types are rarely appropriate for the collection of daylight because they reduce light transmittance. They are sometimes used to control heat gain and the glare caused by the excessive brightness ratios between windows and walls. These three types of glazing do not, however,

solve the problem automatically, because they reduce the interior brightness as much as they reduce the brightness of the view. Thus, the brightness ratios remain the same—as does the glare. Tinted or reflective glazing can reduce glare from view windows only if the interior is also illuminated by other sources, such as skylights, clerestories, or the daylighting glazing above light shelves, and not by the view windows alone. When there are other light sources, reducing the transmission of the view glazing reduces the glare because the reduced brightness of the view window is then closer to the interior brightness (Fig. 13.12a). Of course, electric lights can also increase interior brightness, but using them to reduce the glare from sunlight defeats the whole idea of daylighting.

As mentioned earlier in this chapter in the section on cool daylight, one should use spectrally selective glazing when light but little or no heat is required, as illustrated in Figure 13.12b and curve 3 in Figure 13.12c. In buildings where winter heat is desired, a traditional low-e glazing should be used, since it transmits both the visible and solar infrared (curve 2 in Fig. 13.12c). When neither heat nor much light is required, as in view windows on the east and west facades, then a low-transmission, spectrally selective low-e coating should be used that blocks some light and most solar infrared (curve 4 in Fig. 13.12c). However, avoid dark-tinted glazing, because it can create a gloomy atmosphere. This type of glazing is usually called "low solar heat gain glazing."

Thus, it is no longer appropriate to use the same glazing for all orientations. Instead, an efficient, sustainable design will tune the glazing for each orientation as a function of building type and climate.

Most glass blocks are not especially useful for daylighting because they afford little control over the direction or quality of the light (Fig. 13.12d top). They also do not provide access to views, and they have poor thermal performance. However, one type of glass block is made especially for daylighting design. It is called light-directing because of built-in prisms that refract the light up toward the ceiling for even and deep penetration of daylight into a space (Fig. 13.12d bottom). These light-directing blocks were once very common but are now quite hard to obtain. At least one Japanese firm (Nippon Electric Glass Co.), however, still exports them to the United States.

Translucent glazing material with very high light transmittance is not usually appropriate for window glazing for several reasons. It becomes a source of glare when illuminated by the sun (see Figs. 13.10i and 12.3b). Because it diffuses light in all directions equally, it is not very helpful in improving the illumination gradient across the room. And, of course, translucent glazing does not allow for a view.

On the other hand, translucent glazing materials of relatively low light transmittance can be used successfully for daylighting when the glazing area is quite big. A large area of low-transmittance glazing, especially overhead, creates a large, low-brightness source that will contribute a significant amount of light without glare (Fig. 13.17a). A discussion of translucent walls and roofs will follow later.

Section 9.18 describes various glazing types with an emphasis on shading rather than daylighting. Because shading and daylighting are so intertwined, a good understanding of shading is a prerequisite for understanding daylighting.

To choose the appropriate glazing for any window, it is important to know some of the terminology used. See Sidebox 13.12 for some of the key terms.

Glazing that can change from high- to low-light transmittance is called **dynamic glazing**. Because it neither changes the direction of the light being transmitted nor its spectral selection, its application is mainly for shading and therefore covered in Chapter 9.

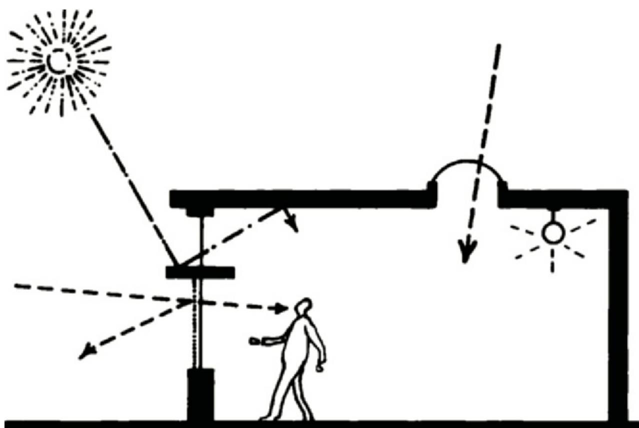


Figure 13.12a Tinted or reflective glazing in the view windows will reduce glare only if the space is lighted by other sources, such as skylights, clerestories, or daylight glazing above the light shelves.

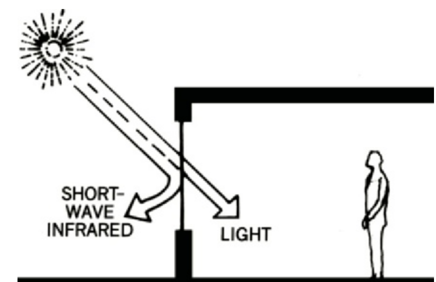


Figure 13.12b Spectrally selective reflecting glazing blocks the sun's infrared radiation while it transmits the visible radiation.

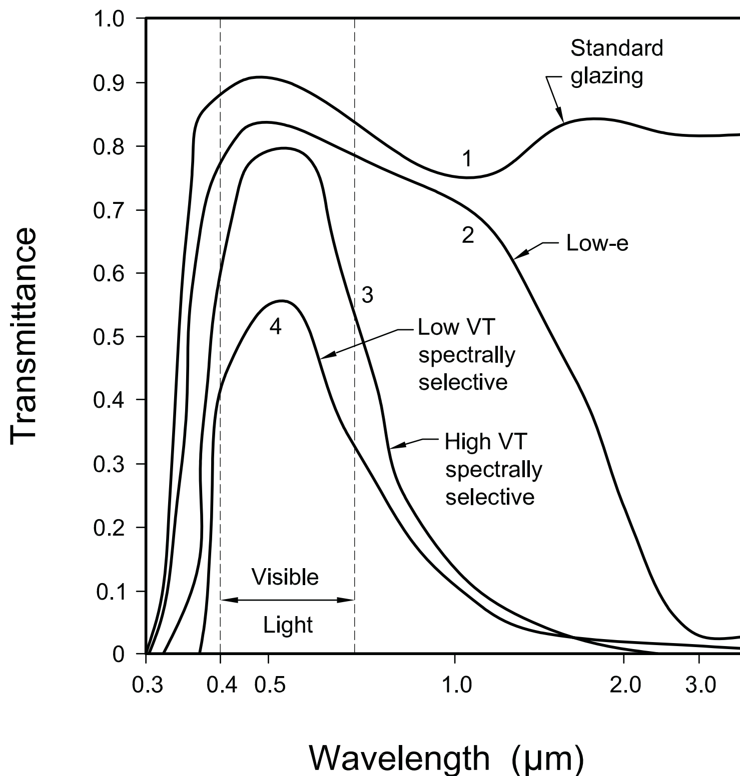


Figure 13.12c Curve 1 represents the performance of ordinary clear glazing. Use high-transmission, low-e glazing (curve 2) when winter heat is a priority. Use high-transmission, spectrally selective glazing (curve 3) when much cool daylight is desired, and use spectrally selective glazing (curve 4) for an east-or west-view window that has inadequate outdoor shading. (After *Residential Windows: A Guide to New Technologies and Energy Performance*, by John Carmody, Stephen Selkowitz, and Lisa Heschong. © 1996 by John Carmody, Stephen Selkowitz, and Lisa Heschong.

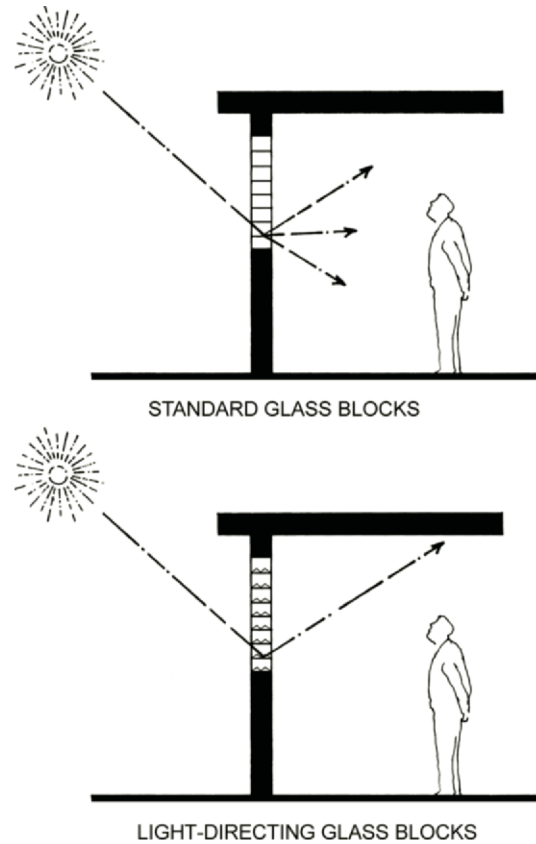


Figure 13.12d Light-directing glass blocks refract the light up to the ceiling. Keep blocks high on the wall to avoid glare.

SIDEBOX 13.12

Terms Useful in Choosing Glazing Systems

Low-e (low-emittance) coating: a very thin metal, metal oxide, or multilayer coating deposited on a glazing surface to reduce infrared heat transfer. Various low-e coatings are available for various applications.

Pyrolytic (hard) coating: a very tough and abrasion-resistant low-e and thin-film coating which can be placed on exposed glass surfaces

Sputter (soft) coating: a low-e silver-based coating that was traditionally delicate and susceptible to damage by abrasion. Consequently, sputter coatings had to be on glass facing protected air spaces. However, new developments are making them much harder.

Spectrally selective coating: a low-e coating largely transparent to light but not to certain infrared radiation.

Surface numbering: to define the surface(s) that have certain coatings, each surface of a glazing system has a number assigned to it. The surface facing outdoors is #1, the indoor side of that pane is #2, etc. Double glazing would have 4 surfaces and triple glazing would have 6.

Rules for Glazing Selection for Daylighting

1. For south glazing:
   a. Use high solar heat gain low-e clear glazing if winter heat is desired.
   b. Use high light-to-solar-gain (LSG) low-e glazing if winter heat is not desired.
2. For east and west glazing:
   a. Minimize glazing area.
   b. Use high LSG low-e glazing in cold climates.
   c. Use low solar heat gain selective low-e glazing in hot climates.
3. For north glazing, use high visible transmittance low-e clear glazing.
4. For horizontal glazing or skylights:
   a. Minimize skylights and maximize clerestories.
   b. Use translucent high solar gain low-e glazing in cold climates.
   c. Use translucent high LSG low-e glazing in hot climates.
5. Clerestory (vertical) glazing:
   a. Same as windows.
   b. Can be translucent.

The best inventions of humankind: fire, the wheel, writing, the venetian blind, and the light shelf!

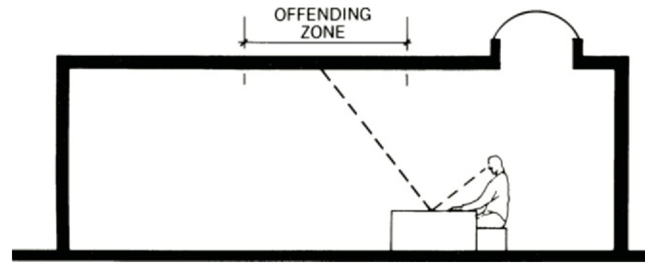


Figure 13.13a Veiling reflections are avoided when skylights are placed outside the offending zone.

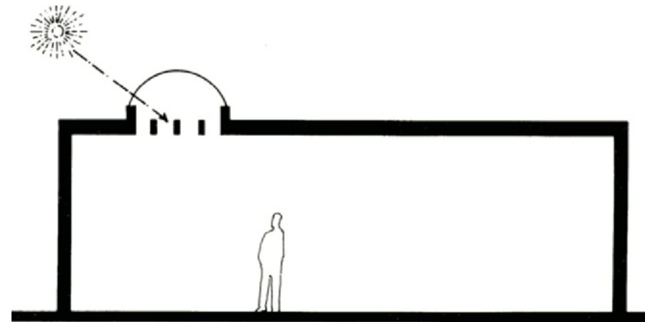


Figure 13.13b A system of baffles can control direct glare and to some extent veiling reflections.

13.13 TOP LIGHTING

Skylights, monitors, and clerestories are all methods of top lighting. The advantages of top lighting are the potential for high-quality and high-quantity illumination over a large area. Unfortunately, top lighting also has some serious drawbacks. It is not a workable strategy for multistory buildings, and since it does not satisfy the need for view and orientation, it should supplement, not replace, windows.

Top lighting, like all lighting from above, can cause direct glare and veiling reflections. These reflections are best avoided by keeping light sources out of the offending zones. This is easiest when the location of the visual task is fixed and the roof openings can be appropriately placed (Fig. 13.13a). Usually, the best solution is to carefully diffuse the light so that there are no bright sources to cause veiling reflections or glare. Either use baffles or banners to shield the light (Fig. 13.13b and Colorplates 16 and 17), or reflect the light off the ceiling (Fig. 13.14f and 13.14g). Both of these strategies also solve the problem of puddles of sunlight falling on the work surfaces. Because skylights behave differently from monitors and clerestories, they are discussed separately.

Use top lighting whenever possible!

13.14 SKYLIGHT STRATEGIES

Skylights are horizontal or slightly sloped glazed openings in the roof. As such, they see a large part of the unobstructed sky and, consequently, transmit very high levels of illumination. Because beams of direct sunlight are not desirable for difficult visual tasks, the entering sunlight must be diffused in some manner. For skylights, unlike windows, translucent glazing can be appropriate since there is no view to block and direct glare can be largely avoided.

A fundamental problem with all skylights is that they face the summer sun more than the winter sun. Thus, they collect much more light and heat in the summer than the winter, which is exactly the opposite of what is needed. In cases where winter heating is not desired, the collected light should be uniform throughout the year. But there is never a situation when more light is desired in the summer than in the winter. As a result, clerestories should be used instead of skylights whenever possible in temperate climates. The situation is somewhat different in the tropics (see Chapter 17). Because skylights are inexpensive and popular, they will be discussed here.

Guidelines

1. *Skylight spacing for uniform lighting*. If there are no windows, the skylights should be spaced as shown in Figure 13.14a. With windows, the skylights can be farther from the perimeter, as shown in Figure 13.14b.
2. *Use splayed openings to increase the apparent size of skylights*. More quantity and higher-quality daylight is collected when openings are splayed (Fig. 13.14c).
3. *Place the skylight high in a space*. A skylight mounted high above a space will enable the light to diffuse before it reaches the floor (Fig. 13.14d). Direct glare is largely prevented, because the bright skylight is at the edge of or beyond the observer's field of view.
4. *Place skylights near walls*. Any wall, and especially the north wall, can be used as a diffuse reflector for a skylight (Fig 13.14e). The bright wall will make the space appear larger and more cheerful. The north wall will balance the illumination from the south window. Avoid puddles of sunlight on the lower parts of the walls.
5. *Use interior reflectors to diffuse the sunlight*. A skylight can deliver very uniform and diffused light when a reflector is suspended under the opening to bounce light up to the ceiling (Fig. 13.14f). Louis I. Kahn used this strategy very successfully in the Kimbell Art Museum (Fig. 13.14g). The light entering a continuous skylight is reflected by a daylight fixture onto the underside of the concrete barrel vault. The result is extremely high-quality lighting. No direct glare results because the daylight fixture shields the skylight from view. Small perforations in the daylight fixture allow some light to filter through, so the fixture does not appear dark against the bright ceiling.

   The author believes that if Louis I. Kahn were alive today and were designing this museum,

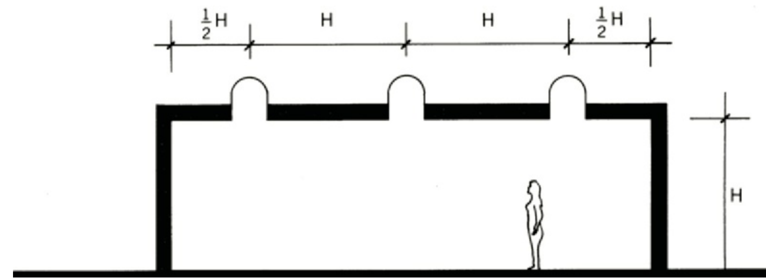


Figure 13.14a Recommended spacing for skylights without windows is given as a function of ceiling height.

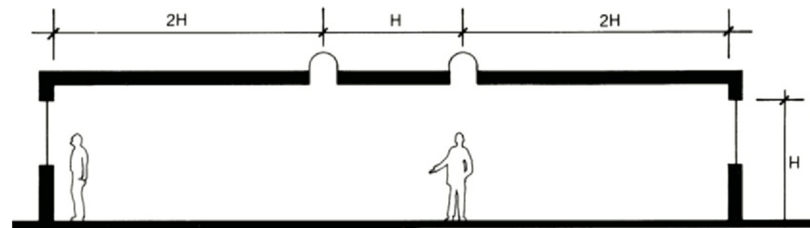


Figure 13.14b Recommended spacing for skylights with high windows is given as a function of ceiling height.

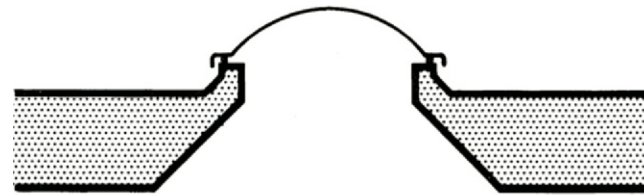


Figure 13.14c Splayed openings distribute light better and cause less glare than square openings.

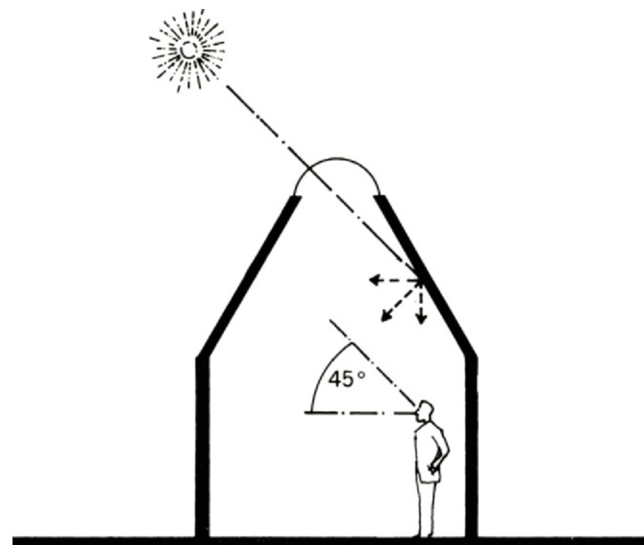


Figure 13.14d In high, narrow rooms, glare from skylights is minimal because the high light source is outside the field of view.

he would use clerestories rather than skylights in order to avoid the large summer heat gain and to collect more winter sun.

The Menil Collection in Houston, Texas, designed by architect Renzo Piano, in 1982, uses skylights with diffusing baffles in all parts of the building except the two-story section (Fig. 13.14h). The skylight glazing is slightly sloped for drainage (Fig. 13.14i). The ferro-cement baffles were carefully designed to keep all direct sunlight out of the building. A weakness of this design is the use of skylights, which cause overheating in the summer. In his latest design, the addition to the High Museum in Atlanta, Georgia (2005), Renzo Piano avoided this problem by using exterior baffles (shading devices), which prevent any direct sunlight from entering and create very uniform illumination inside (Figs. 13.14j and 13.14k).

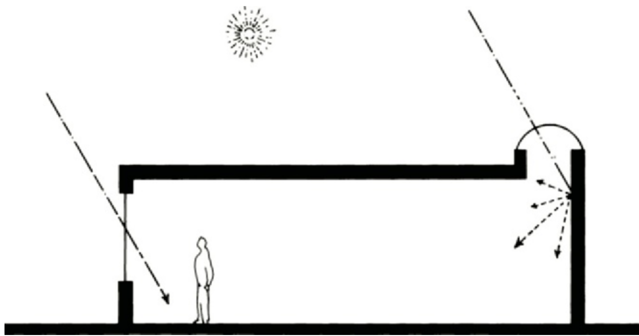


Figure 13.14e Place a skylight in front of a north wall for more uniform lighting and less glare.

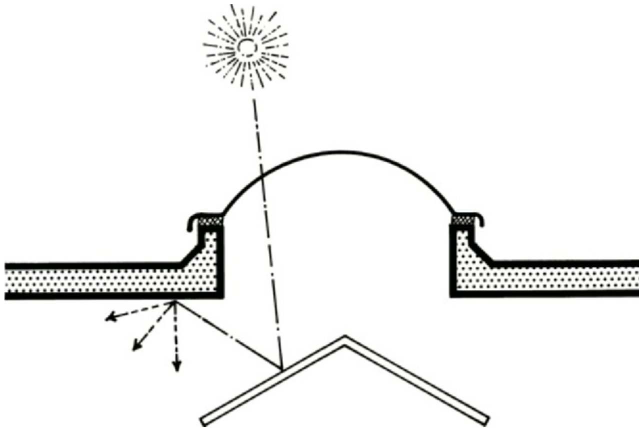


Figure 13.14f Use interior reflectors (daylight fixtures) under skylights to diffuse sunlight and reduce glare.



Figure 13.14g In the Kimbell Art Museum, Fort Worth, Texas, Louis I. Kahn successfully used daylight fixtures to diffuse light and to eliminate direct glare from skylights.



Figure 13.14h All gallery spaces in the Menil Collection, designed by Renzo Piano, are daylit except for those under the second story. However, the color of the daylight varies for those areas in direct sunlight and those areas in shade that are receiving only north skylight (see Colorplate 16).



Figure 13.14i The glazing in the Menil Collection is above the baffles, which allow only soft, diffused daylight to enter.



Figure 13.14j In the design of the addition to the High Museum in Atlanta, Georgia, Renzo Piano used light scoops to control the collection of sunlight. The opening at the base of each light scoop is for reducing wind loads.



Figure 13.14k No direct sunray can ever enter the High Museum in Atlanta, Georgia. The evenness of the diffused daylighting is most obvious where the partition meets the ceiling—almost no scallops.



Figure 13.14l In the addition to the Chicago Art Institute, Renzo Piano uses exterior baffles to control the amount and direction of daylight. The baffles (louvers) face toward the north.

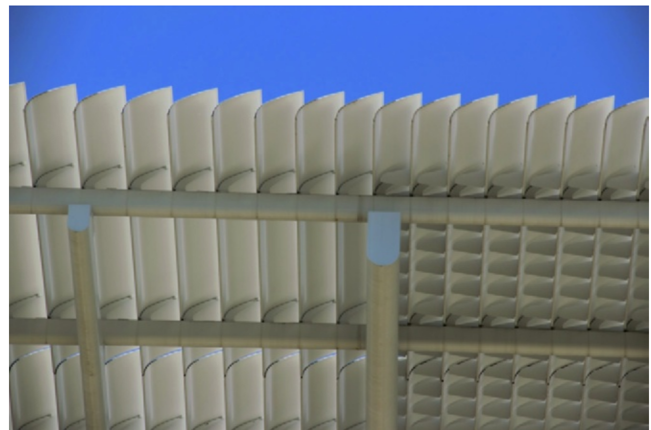


Figure 13.14m To prevent the east and west sun from outflanking the baffles in the Chicago Art Institute addition, a second set of baffles was added over the skylight and east and west overhangs.

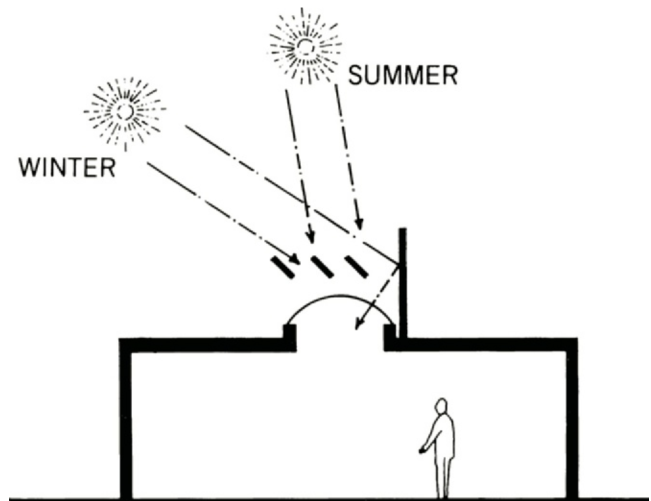


Figure 13.14n Shade the skylight from some of the summer sun, and use a reflector to increase the winter collection.

Recently, Renzo Piano also added a wing to the Chicago Art Institute in which he again used outdoor baffles to shield the horizontal glazing (Figs. 13.14l and 13.14m). The baffles are aimed to the north sky, which is widely considered the best light for displaying artwork. However, that decision prevents collecting more sun in the winter to help heat the building. If the outdoor baffles faced south, indoor diffusers and movable shades could control the quality and the quantity of light falling on the artwork while still collecting the winter heat.

6. *Use exterior shades and reflectors to improve the summer/winter balance*. Shade the skylight from the summer sun, and use reflectors to increase the collection of the winter sun (Fig. 13.14n).
7. *Quantity controls*. Some spaces, such as classrooms when using audiovisuals, need to control the amount of daylight any time of the year. Figure 13.14o shows a skylight with operable louvers that can be controlled manually or automatically by photo sensors to maintain the daylight illumination at a constant level. There is a commercial product called Intelaglas that has movable louvers inside a transparent sandwich panel.
8. *Use steeply sloped skylights to improve the summer/winter balance*. Since horizontal skylights collect more light and heat in summer than in winter, skylights steeply sloped toward the north or south will supply light more uniformly throughout the year (Fig. 13.14p). As the slope is increased, the skylights eventually turn into monitors or clerestories, as described in the next section.
9. *Use sunlight for dramatic effect*. In lobbies, lounges, and other spaces without critical visual tasks, use sunlight and sun puddles to create delight. Splashes of sunlight moving slowly across

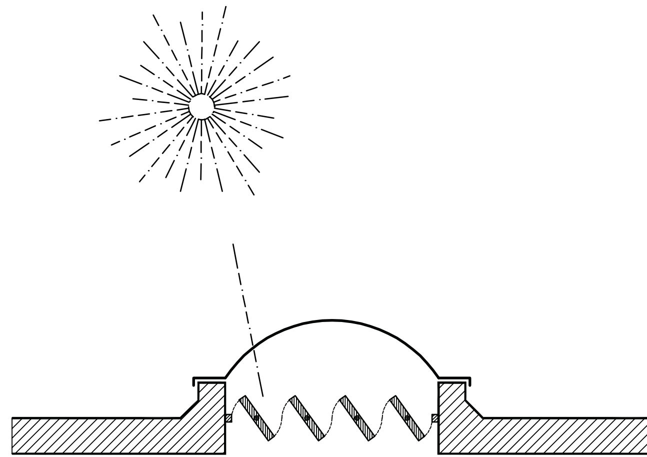


Figure 13.14o Some spaces, such as offices, need to modulate the light level, while other spaces, such as classrooms, need to block all light when viewing audiovisuals. Operable louvers, to adjust the light levels, can be controlled manually or automatically as needed.

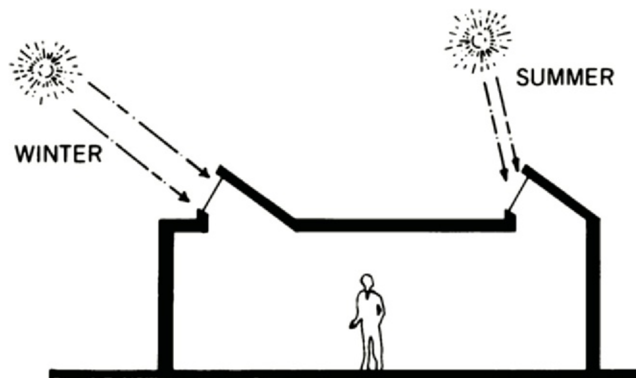


Figure 13.14p Steeply sloped skylights perform better than horizontal ones because they collect more winter sun and less summer sun.



Figure 13.14q Highly reflective glazing and a gossamer space frame filter the light entering the Crystal Cathedral, Garden Grove, California, designed by Johnson and Burgee.



Figure 13.14r Overheating problems in the Crystal Cathedral, Garden Grove, California, are minimized by the highly reflective glazing and large sections of window wall that can be opened. Only one of many operable panels is open (see left center).



Figure 13.14s For a dramatic effect, I. M. Pei allowed direct sunlight to enter the central circulation space of the East Wing, National Gallery of Art, Washington, D.C. However, to reduce overheating from the large skylight, a fret of white parallel stripes was attached to the glazing.

surfaces can create dramatic effects and display the passage of time. To minimize summer overheating, use either small skylights or large skylights with reflective glazing, **frets** painted on the glass, or covered with PV cells (see Fig. 8.11b) to block a significant amount of the sun.

Perhaps no modern building uses daylighting as exuberantly as the Crystal Cathedral in Garden Grove, California (Fig. 13.14q). The walls and roof are all glass, supported by a gossamer space frame. The light is filtered first by the highly reflective glazing (8 percent transmittance) and then again by the white space frame. From the outside, the building is a large mirror mainly reflecting the blue sky (Fig. 13.14r). Overheating is minimized by the low-transmission glass, by large wall and roof panels that can open for natural ventilation, by stratification, and by the fact that the building is primarily used either in the morning or in the evening in the rather mild climate found just south of Los Angeles.

In the East Wing of the National Gallery, Washington, D.C., I. M. Pei used skylights in the form of tetrahedrons to create dramatic daylighting in the atrium lobby (Fig. 13.14s). To limit the solar gain through the very large skylight, a fret of parallel white lines was applied to the glass.

13.15 CLERESTORIES, MONITORS, AND LIGHT SCOOPS

Clerestories, monitors, and light scoops are by definition all raised above the main roof in order to bring light to the center of a space (Fig. 13.15a). The word "monitor" is ordinarily used when the windows face more than one direction and are operable (Fig. 13.15b), while the term "light scoop" is ordinarily used when the clerestory windows face one direction only and the opposite side is curved to reflect the light down (Fig. 13.15c). Clerestories have been used in architecture for at least 4000 years to bring daylight into the central area of large spaces. Egyptian hypostyle halls had taller columns in the center to raise the roof, thereby creating a clerestory for light and ventilation.

The vertical or near-vertical glazing of clerestories has the characteristics of windows rather than skylights. When they face south, clerestories have the desirable effect of collecting more sunlight in the winter than in the summer. Vertical south-facing openings can also be shaded easily from unwanted direct sunlight. North-facing clerestories deliver a low but constant light with little or no glare, while east and west ones should usually be avoided because of the difficulty in shading the low sun, and because they receive more summer sun than winter sun.

Another advantage of clerestory lighting is the diffused nature of the light, which results because much of the entering light is reflected off the ceiling when a white or very light-colored roof is used (Fig. 13.15d). Since the light is easily diffused once inside, the glazing can be transparent.

The main disadvantage of any vertical opening is that it sees less of the sky than a horizontal opening and, consequently, collects less light on an annual basis. As with skylights, direct glare and veiling reflections can be serious problems. The following are some of the more common strategies for clerestories, monitors, and light scoops.

Guidelines for Clerestories

1. *Orientation*. Face openings south to get the most winter solar heating and good lighting all year. Design openings carefully to



Figure 13.15a These south-facing clerestories illuminate classrooms at the Durant Middle School, Raleigh, North Carolina. The sawtooth arrangement keeps one clerestory from shading the next, and the sloped ceiling more efficiently directs the light down. Innovative Design, Architect.

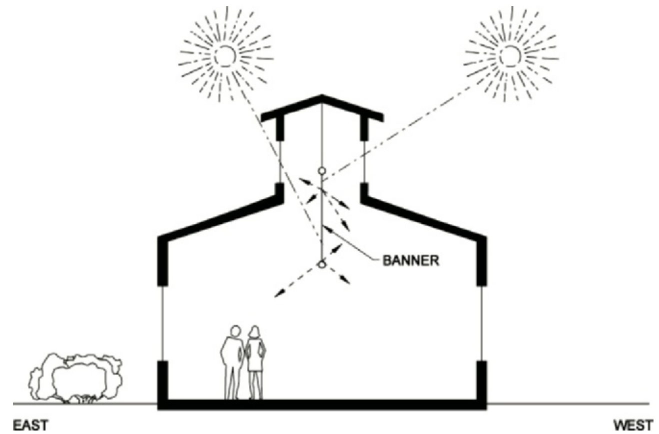


Figure 13.15b Monitors usually ventilate and light the center of large spaces. A banner is an effective technique for diffusing the sunlight (see also see Colorplate 17).

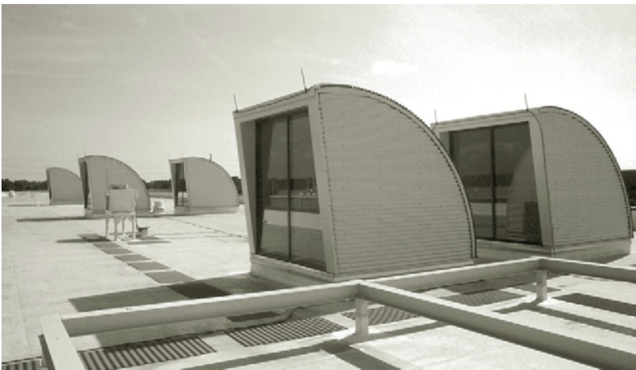


Figure 13.15c These light scoops on the roof of the Florida Solar Energy Center in the town of Cocoa face north because passive solar heating is not required for this building in that climate.

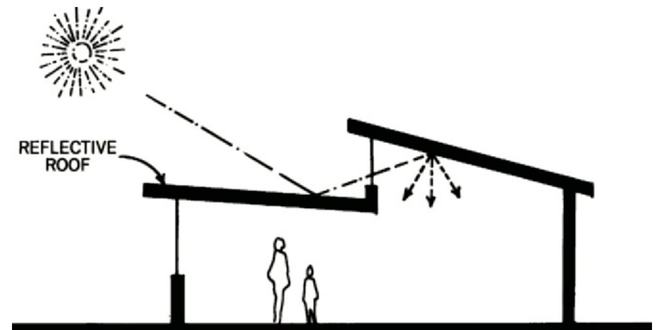


Figure 13.15d Use a very reflective roof to maximize the diffused light entering the building.

prevent problems associated with direct sunlight. In extremely hot climates with no winters, north clerestories are preferred, while in hot climates with short winters, a combination of north and south glazing might be best. Avoid east and west glazing as much as possible.

2. *Spacing*. Figure 13.15e illustrates spacing for typical clerestories.
3. *Reflective roof*. Use a high-reflectance white roof to reflect more light through the clerestory glazing. To maximize winter collection, a specular reflector can be mounted on the roof just outside the glazing. Once indoors, the light needs to be reflected off a

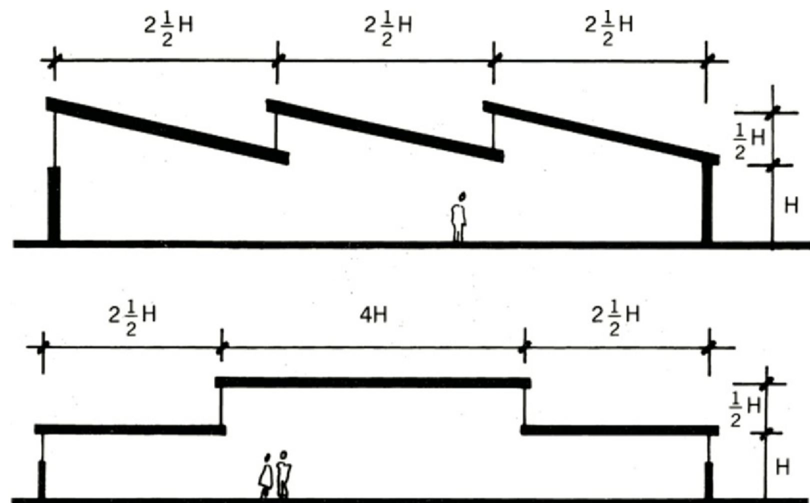


Figure 13.15e Typical spacing of clerestories is shown as a function of ceiling height. It is usually best to have clerestories face either north or south, depending on the climate.

high-reflectance flat white ceiling (Fig. 13.15d).

4. *Suncatcher baffles*. Use suncatcher baffles outside of north clerestories to increase light collection on clear, sunny days (Fig. 13.15f).

   Although east and west clerestories are not usually recommended, their performance can be greatly improved via suncatcher baffles. Ordinarily, east clerestories receive too much morning sun and not enough afternoon light. A suncatcher can produce a more balanced light level by shading some of the morning sunlight while increasing the afternoon reflected light (Fig. 13.15g). Of course, the same is true for west clerestories.

5. *Reflecting light off interior walls*. Walls can act as large, low-brightness diffusers. A well-lit wall will appear to recede, thereby making the room seem larger and more cheerful than it actually is. Furthermore, glare from a direct view of the sky or the sun can be completely avoided (Fig. 13.15h). Le Corbusier used this technique in Notre Dame du Haut, where the towers act as clerestories. As a result, the interior walls of the towers glow with a soft light (Fig. 13.1k).

6. *Diffusing baffles*. Use diffusing baffles to prevent puddles of sunlight on work surfaces, to spread the light more evenly over the work areas, and to eliminate glare from the clerestory (Fig. 13.15i). The baffle spacing must be designed both to prevent direct sunlight from entering the space and to prevent direct glare in the field of view below 45°. The baffles should have a matte, high-reflectance finish or be highly translucent. The baffles are often made of a light-colored thin cloth hanging from a pole or cable. Figure 13.15j shows how the light from a clerestory is diffused by hanging baffles.

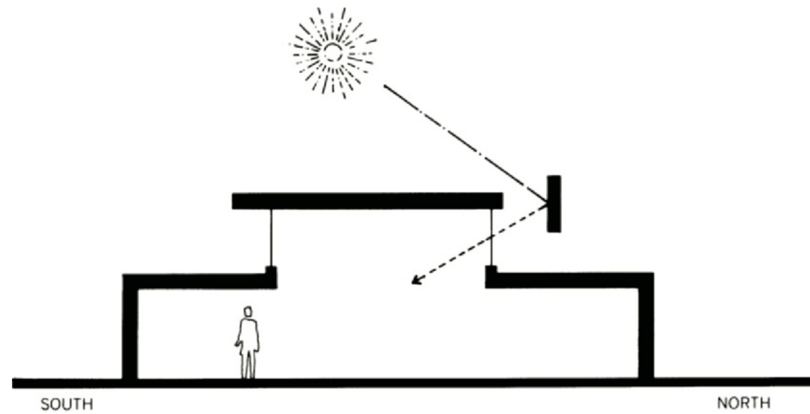


Figure 13.15f A suncatcher baffle outside a north window can significantly increase daylighting on a sunny day. (After Lam, *Sunlighting as Formgiver for Architecture*, 1986.)

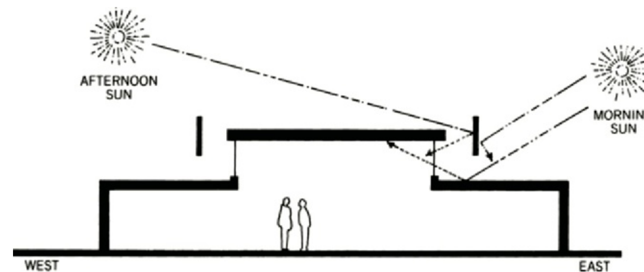


Figure 13.15g Suncatcher baffles can greatly improve the performance of east and west clerestories. (After Lam, *Sunlighting as Formgiver for Architecture*, 1986).

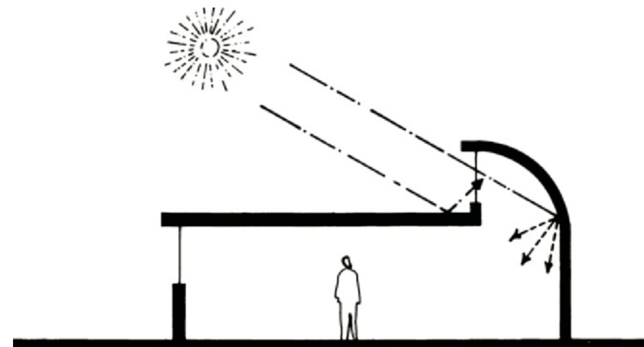


Figure 13.15h Reflect clerestory light off an interior wall. South-facing clerestories work best in this regard.

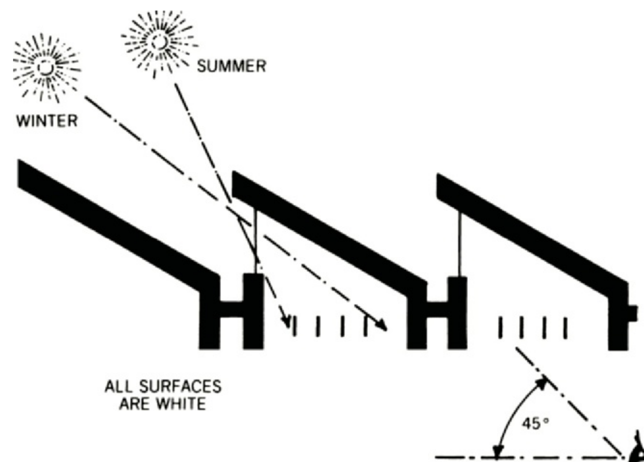


Figure 13.15i The baffles for the public library in Mt. Airy, North Carolina, not only prevent direct sunlight from entering, but also prevent glare within the normal field of view.



Figure 13.15j These baffles prevent glare and diffuse the light entering from a south-facing clerestory at the Durant Middle School, Raleigh, North Carolina. (Innovative Design, Architect.)

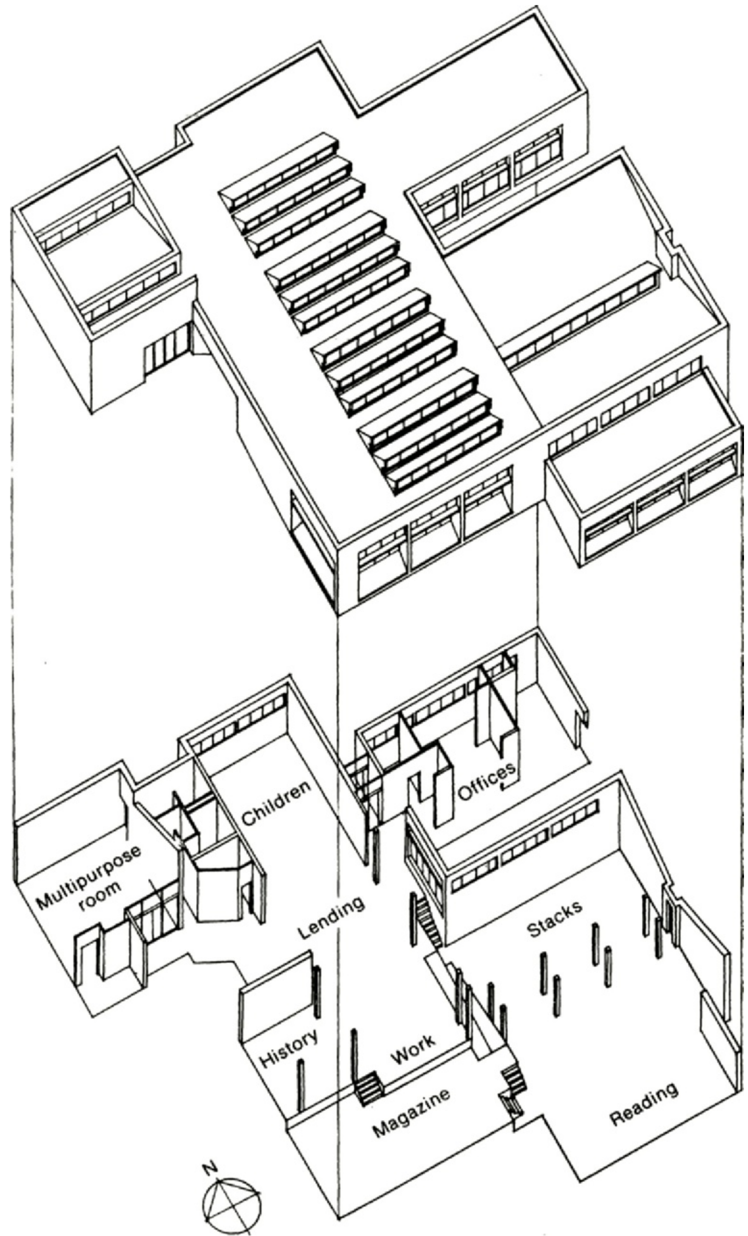


Figure 13.15k Axonometric view of the Mt. Airy Public Library in North Carolina. Architects: Edward Mazria Assoc. and J. N. Pease Assoc. (From *Passive Solar Journal*, Vol 3 (4). © American Solar Energy Society.)

The Mt. Airy Public Library in North Carolina is an excellent example of a building largely daylit by clerestory windows. The axonometric view in Figure 13.15k shows the location of the south-facing clerestories, and Figure 13.15l illustrates how the direct sunlight is captured and diffused. Also, note how the electric lights and mechanical equipment are integrated into the daylighting system (Fig 13.15m). This building also uses light shelves on the windows.

7. Structural elements acting as baffles. Alvar Aalto, the master of daylighting, made extensive use of clerestories and light baffles in the Parochial Church of Riola, Italy (Fig. 13.15n). He used the concrete structure to create both the light scoops and the baffles (Fig. 13.15o). Although his light scoops face north for cool, constant light, a good case could have been made for them facing south or especially east (Fig. 13.15p). East-facing light scoops might seem contradictory, given everything said before, but not if one considers the building type, a church that is used primarily on Sunday mornings and rarely in the afternoon.

On the outskirts of Manila in the Philippines, the author spotted a most interesting building. It turned out to be a church daylit by clerestories formed by concentric but offset arches (short barrel vaults) oriented along a north-south axis that prevented

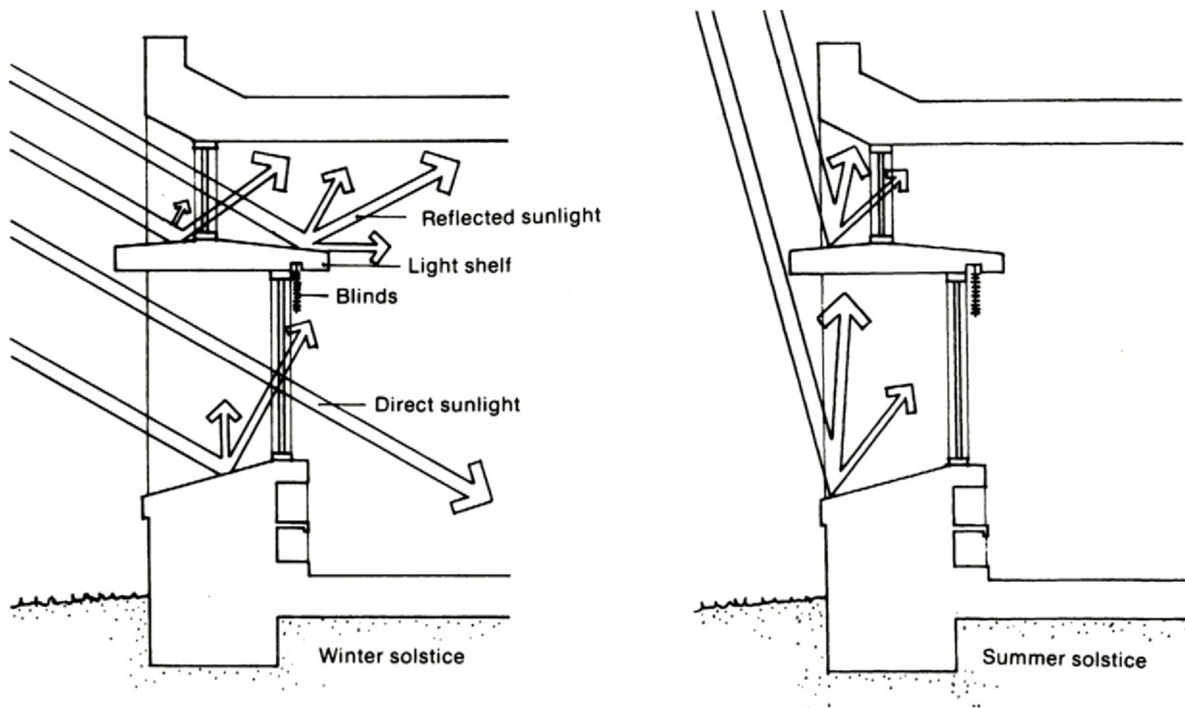


Figure 13.15l Sections through south windows of the Mt. Airy Public Library in North Carolina. More reflected sunlight can enter in the winter than the summer. (From *Passive Solar Journal*, Vol. 3(4). © American Solar Energy Society.)

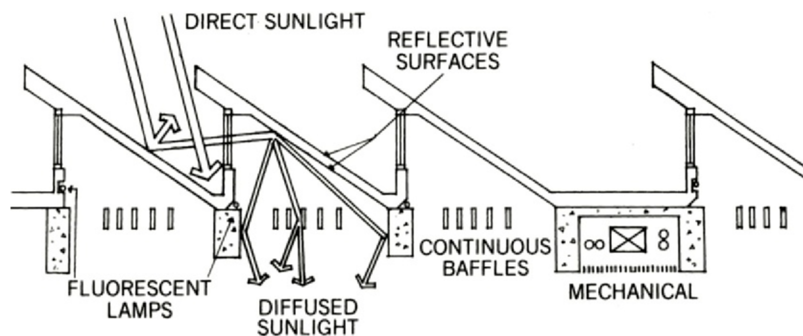


Figure 13.15m Section through the clerestory of the Mt. Airy Public Library, in North Carolina. (From *Passive Solar Journal*, Vol. 3(4). © American Solar Energy Society.)



Figure 13.15n Clerestories can also be used in the form of light scoops. The Parochial Church of Riola, Italy (1978), designed by Alvar Aalto, uses bent concrete frames to support the roof and to block the glare from the light scoops. (Photograph by William Gwin.)

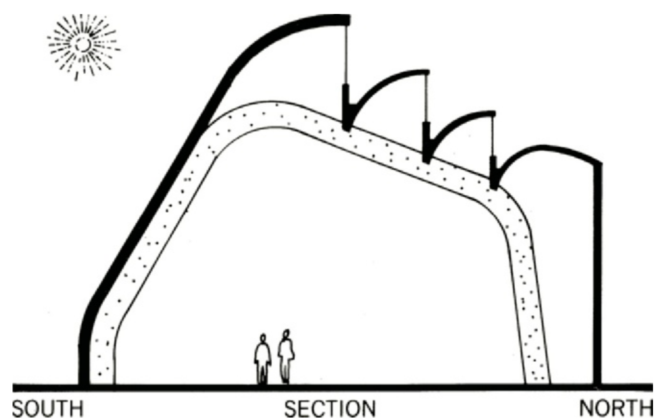


Figure 13.15o A section of the Parochial Church of Riola, Italy.



Figure 13.15p The light scoops of the Parochial Church of Riola, Italy, collect constant and cool north light. (Photograph by Clark Lundell.)



Figure 13.15q Deep arches are offset to create a series of clerestories in this church outside of Manila in the Philippines. Because the arches are on a north-south axis, no direct sunlight is ever able to enter. The north and south sides are nearly identical because the building is only 14 degrees from the equator.



Figure 13.15r An interior view of the deep arches or narrow barrel vaults of the Manila church.

any direct sunlight from entering (Figs. 13.15q and 13.15r).

8. *Quantity controls*. Many toplit spaces, such as classrooms when using audiovisuals, need the ability to reduce or eliminate daylighting. Since clerestories have most of the properties of windows, venetian blinds, vertical blinds, roll-up shades, or curtains can be effectively used. All of the devices are easily operated remotely through electrical or mechanical means.

Use clerestories instead of skylights whenever possible!

13.16 SPECIAL DAYLIGHTING TECHNIQUES

The following daylighting strategies may be useful for special lighting problems:

1. *Light wells or shafts*. Light wells become more efficient as the width-to-depth ratio increases because less light is absorbed by the reduced number of reflections (Fig. 13.9f). If the well walls were very reflective, more light would be transmitted or the well could be made narrower for the same light transmission. With modern, very reflective, specular (mirrored) surfaces, which absorb as little as 2 percent at each reflectance, it is possible to successfully transmit light one story with fairly small light wells. Moshe Safdie and associates used such light shafts in the National Gallery of Canada (Fig. 13.16a). Physical models were used to prove the viability of this strategy.
2. *Tubular skylights*. Duct-like tubes are commercially available with highly reflective, specular inner surfaces that transmit about 50 percent of the outdoor light through the attic (Fig. 13.16b). The amount of light depends largely on the diameter and

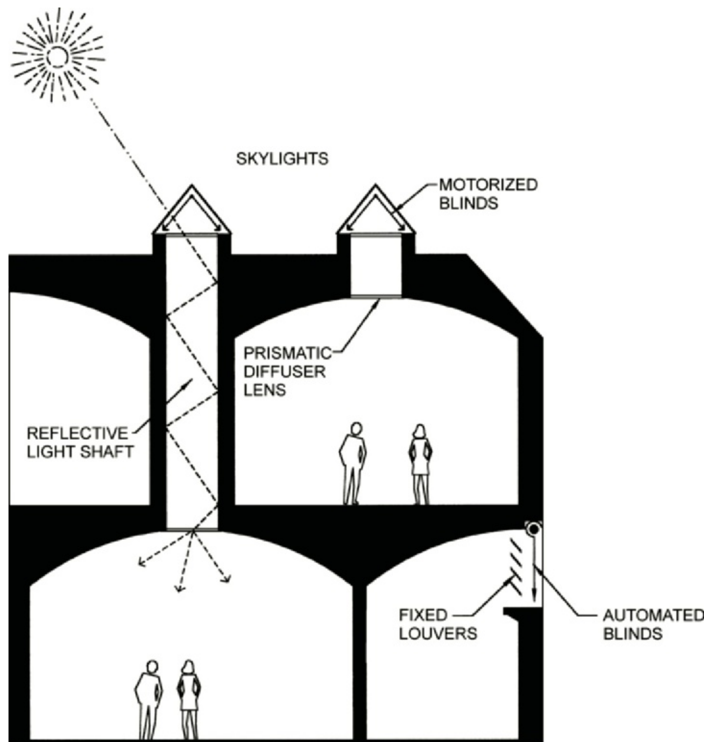


Figure 13.16a Light shafts with highly reflective specular surfaces bring daylight through the second floor to the ground floor galleries at the National Gallery of Canada in Ottawa, Ontario, Canada, designed by Moshe Safdie and Associates.

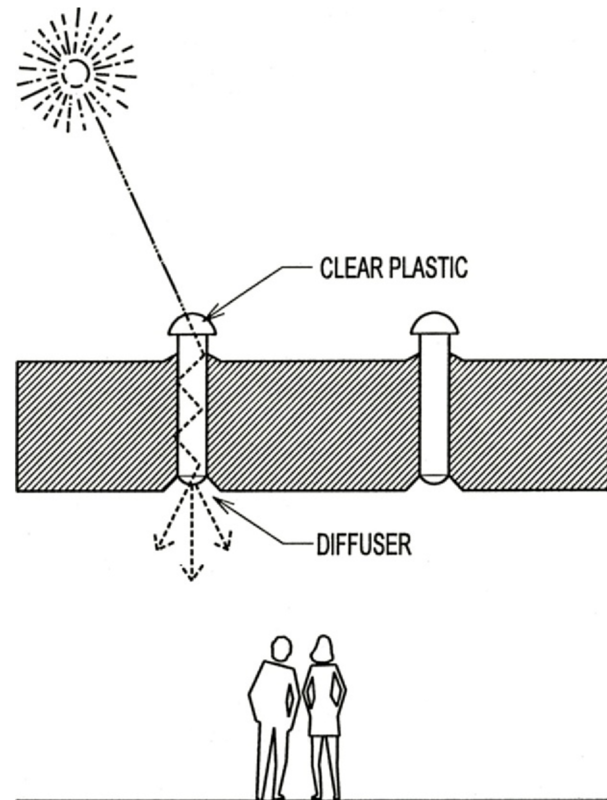


Figure 13.16b Tubular light shafts are most appropriate for bringing daylight into the interior areas of existing buildings. When used in new construction, the lower opening should be splayed as much as possible.

length. Circular tubes are available in a range of sizes from 8 to 24 in. (20 to 60 cm) in diameter, and square tubes are as large as 4 ft^2 (1.2 m^2). Although they are an economic way to add light shafts to one-story, gabled, or flat-roofed buildings, the light distribution is not much better than that of a ceiling-mounted, circular, fluorescent lamp. Both the quantity and quality of the lighting are improved by splaying the ceiling around the light tube.

3. *Skylights with dynamic mirrors*. Several companies now make skylights with built-in rotating mirrors to reflect the sun down into the building (Fig. 13.16c). An electric motor powered by its own PV panel turns the mirror to track the sun, thereby collecting more daylight early and late each day as well as during the winter.
4. *Beamed daylighting*. A mirror mounted on a heliostat, which is a sun-tracking device, reflects a vertical, concentrated beam of light through the roof regardless of the sun's position. Because the sun enters the building as a vertical narrow beam, it can be easily utilized. When large heliostats are used to illuminate a whole section of a building, the technique is known as beamed daylighting. The Civil/Mineral Engineering Building at the University of Minnesota in St. Paul exemplifies this concept. Mirrors and lenses are used to beam sunlight throughout the building (Fig. 13.16d). Where light is required, a diffusing element intercepts the beam and scatters the light.

   Figure 13.16d also shows how a similar type of optical system can be used to transmit views of the outdoors deep into the building or underground. The Hong Kong Bank, designed by Foster Associates, uses a one-axis heliodon to reflect a beam of sunlight horizontally into the building (Fig. 13.16e). When the beam hits the tilted mirrors at the top of the atrium, sunlight is reflected down to the floor of the atrium deep inside the building (Fig. 13.16f).
5. *Fiber optics and light pipes*. Unlike the above-mentioned systems, which use surface reflections to conduct light, fiber optics and light pipes use the much more efficient phenomenon of total internal reflection. These light guides are illuminated on one end with daylight or an electric light that is almost parallel to the light guide. Since diffused skylight cannot be focused, these light guides work only with sunlight. A heliostat (Fig. 13.16g) is used to track

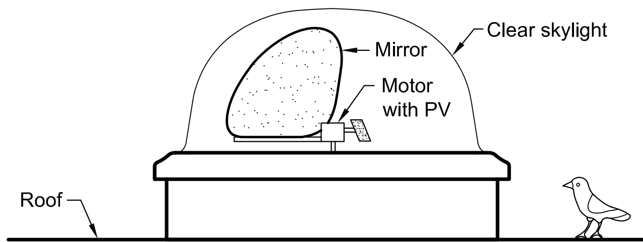


Figure 13.16c Skylights are now available with their own rotating mirror to collect more sun in early morning and late afternoon than is possible with static skylights. The mirror tracks the sun by means of a motor powered by its own PV panel.

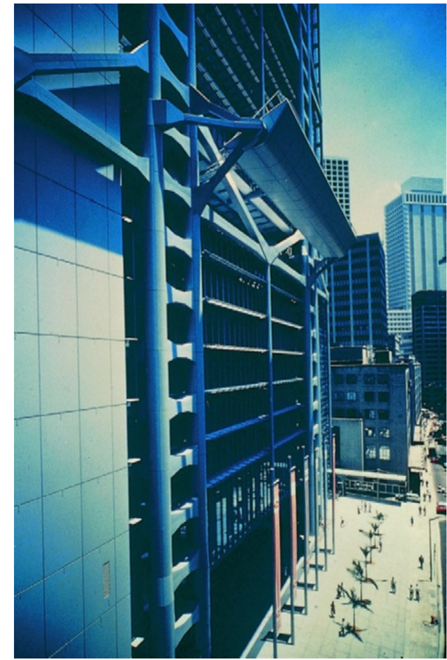


Figure 13.16e A giant one-axis heliostat reflects sunlight into the lobby of the Hong Kong Bank. (Courtesy of Foster Associates. © Ian Lambot, photographer.)

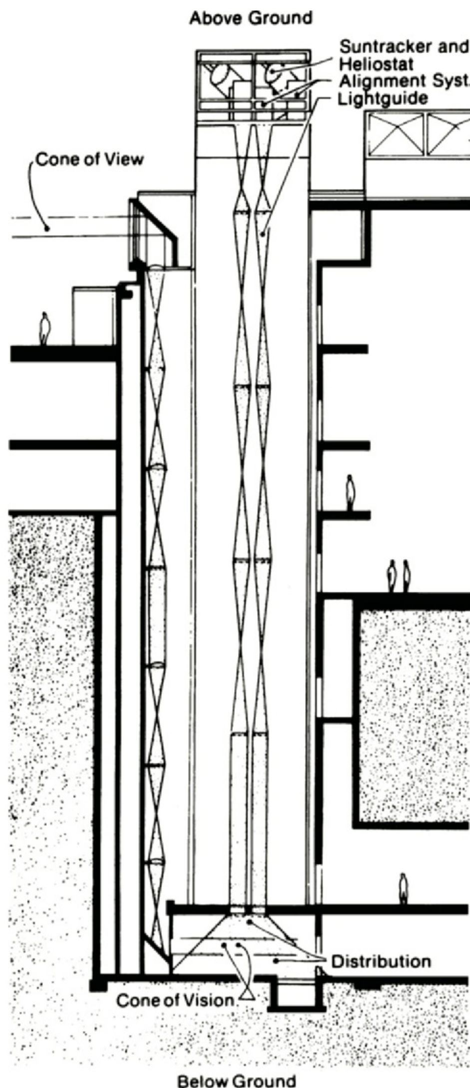


Figure 13.16d The Civil/Mineral Engineering Building at the University of Minnesota in St. Paul uses beamed daylighting to light underground areas of the building. Images of the outdoors can also be beamed to the far interior or underground. (From *Building Control Systems* by V Bradshaw, © John Wiley & Sons, Inc., 1985.)

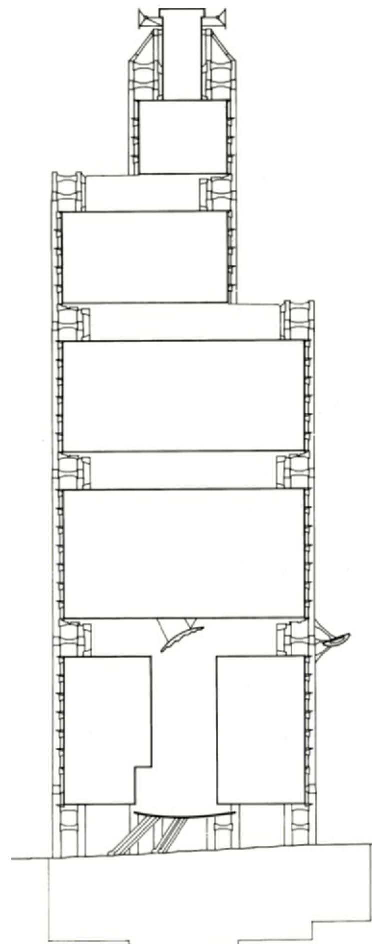


Figure 13.16f This section of the Hong Kong Bank shows how the heliostat reflects sunlight onto a mirror hanging at an angle from the ceiling of the ten-story-high lobby. The sunlight is thus reflected down to the otherwise dark lobby floor. (Courtesy of Foster Associates.)

the sun and reflect the sunrays as a narrow beam into the ends of the light guides, which can be made of either fiber optics or light pipes.

Fiber optics uses thin glass or plastic fibers or plastic rods to conduct light very efficiently by total internal reflection. Because the fibers or rods are thin, they can make fairly sharp turns. Thus, light is conducted almost as easily as electricity is conducted in wires. When the light gets to the end of the fiber, a fiber-optic lighting fixture will create the desired illumination pattern. Like electric lighting fixtures, fiber-optic fixtures can be made in the whole range from spot lighting to linear diffusers.

The Oak Ridge National Laboratory has developed a complete fiber-optic system that is now commercially available. They call this system hybrid solar lighting because it uses not only the visible part (45 percent) but also the short-wave (solar) infrared part of the solar spectrum (50 percent). The heliostat divides the solar radiation, with light directed into the optical fibers or rods and the infrared radiation directed to PV cells (Fig. 13.16h). Thus, the indoor hybrid fixtures have both electric lamps powered by PV and optical diffusing "lamps" powered by light. In this system, a 4 ft (1.2 m) diameter heliostat can illuminate about 1000 ft^2 (90 m^2) of floor area.

Light pipes are hollow, duct-like light guides made of prismatic plastic film that transmit light by total internal reflection, unlike the tubular skylights mentioned above, which use surface reflection. Since light pipes are essentially straight elements, mirrors are used to change direction. Figure 14.12a and 14.12b show how light pipes and fiber optics work with electric light sources.

6. *Prismatic Systems*. Prismatic glass tiles were a popular daylighting product in the early twentieth century. The tiles were used above windows to refract daylight farther indoors (Fig. 13.16i). Their indoor faces consisted of triangular grooves that acted like prisms, while their outdoor faces came with various decorative patterns, one of which was designed by Frank Lloyd Wright. Because they perform a similar function to light shelves, there is renewed interest in using them. For more information see "Web Sites" under "Resources" at the end of this chapter. Also see the references Baker et al. (1993) and Willmert (1999) at the end of this chapter for more information on prismatic systems.

7. *Glass Floors*. In the nineteenth century, glass paving blocks were



Figure 13.16g This commercially available heliostat feeds sunlight into a fiber-optic bundle to illuminate a series of small displays indoors.

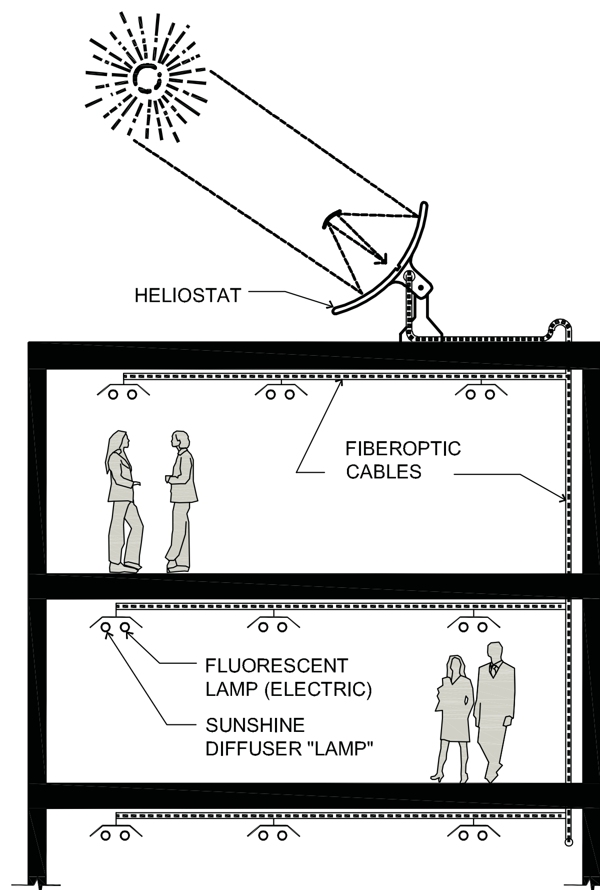


Figure 13.16h In the hybrid solar lighting system, the large heliostat mounted mirror focuses the full solar spectrum on a cap that not only converts the solar infrared to electricity with PV cells but also reflects the visible radiation (light) into the ends of the fiber-optic system. The indoor hybrid lighting fixtures have both electric lamps powered by the PV and diffuser "lamps" powered by the optical fibers.

commonly used to enable light to reach basements. In some of the older commercial areas of New York City, one can still walk on glass-block-embedded sidewalks that have withstood a century of trucks parked on them. Although glass blocks are making a comeback mostly for stylish reasons, they are still a wonderful way to bring light from one floor to the next (Fig. 13.16j).

Because of the brittle nature of glass, the blocks had to be small so that the failure of one unit would not result in a serious overall failure. Today, laminated glass can safely span large distances. As in automobile windshields and bulletproof glass, the failure of one or more glass laminations does not result in a catastrophic failure of the whole unit. Since glass has become a predictable material, engineers can calculate the thickness and number of laminations based on the size of the glass floor panel and its loading. Glass floors in block or panel form can be a powerful tool for transmitting daylight to lower floors (Fig. 13.16k).



Figure 13.16j Glass block pavers can transmit light deep into buildings, as here at the Allen Lambert Galleria, Toronto, Ontario.

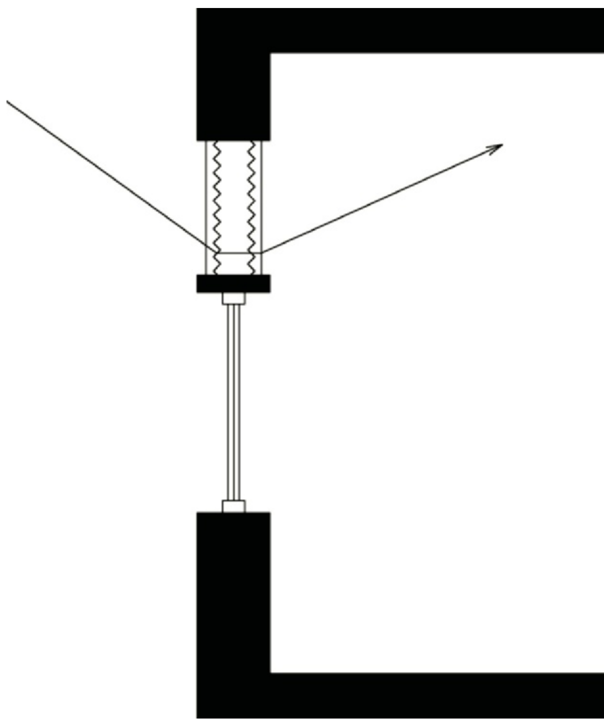


Figure 13.16i Prismatic glazing tiles refract light farther indoors.

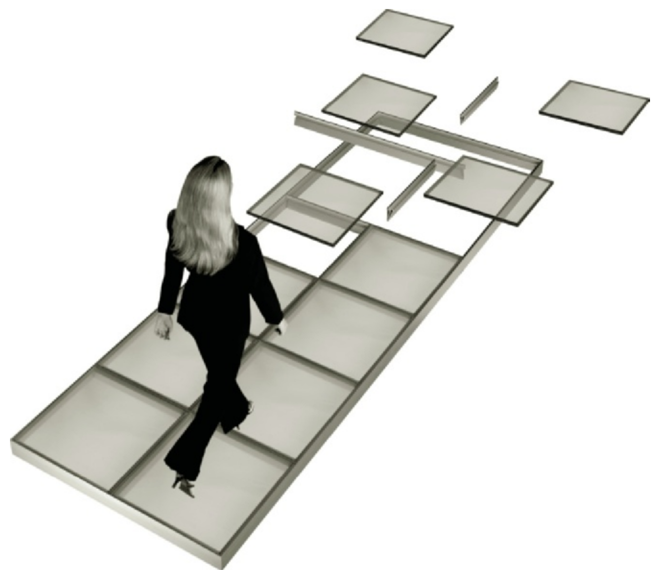


Figure 13.16k Laminated glass floors and stair treads allow daylight to reach lower levels. The glass is usually textured or diffusing for reasons of modesty. (Courtesy of Innovative Building Products, Inc.)

13.17 TRANSLUCENT WALLS AND ROOFS

Most translucent walls and roofs are made of either fabric membranes or composite panels. Membrane tension structures are most appropriate for large spaces with long spans. The translucent membranes provide a very diffused, low-brightness, low-glare, large-area light source. Unfortunately, none of the available translucent-membrane materials has a very good insulating value; consequently, membrane roofs are appropriate only for special building types.

Many stadiums, tennis courts, and other similar facilities are now covered with these translucent membranes. They are usually made of a Teflon- or silicon-coated fiberglass fabric. Even though the light transmittance of those fabrics is often less than 10 percent, abundant high-quality light is available inside because of the very large area of the translucent material. The Denver Airport is an excellent example of the high-quality daylight that filters through such membranes (Fig. 13.17a). Overheating is avoided because the white membrane reflects about 90 percent of the solar radiation (Fig. 13.17b).

A new and exciting application for membrane tension structures is covering a whole campus (Fig. 13.17c). The membrane roof protects windows, walls, roofs, and spaces between buildings from too much sun both in terms of quantity and quality. It is almost like placing the whole campus under a grove of giant shade trees, and unlike shade trees, the membrane allows people to move between buildings without getting wet.

Sometimes double membranes are used to increase the insulating value of the skin to a point at which heating becomes feasible, but a double membrane with an R-value of about 2 is still a poor thermal envelope.

For good thermal resistance with translucency, a composite sandwich panel system is appropriate (Fig. 13.17d). Panels with only air spaces

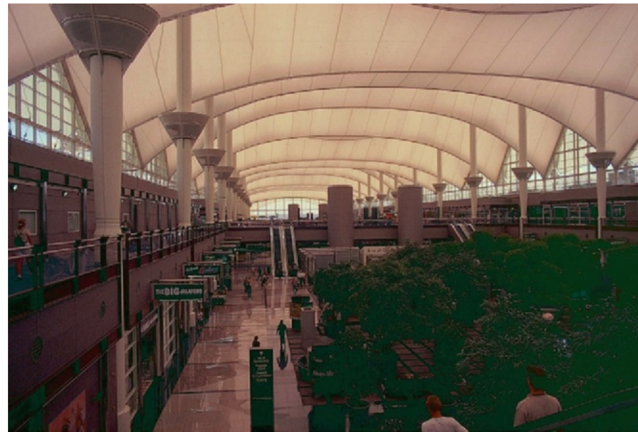


Figure 13.17a Although the roof membrane of the Denver Airport Terminal Building has very low transmittance, there is ample quality daylight because of the large-area, low-brightness translucent roof.



Figure 13.17b Overheating is minimized because about 90 percent of sunlight is reflected off the white membrane. Furthermore, the high ceiling enables the heat to rise, which is an advantage in the summer but a disadvantage in the winter.



Figure 13.17c The whole campus of Lasalle College of the Arts in Singapore is protected by a membrane tension structure.

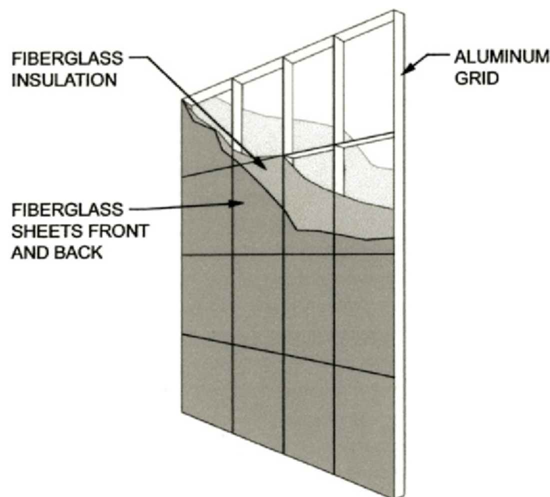


Figure 13.17d As the thermal resistance of translucent, composite sandwich panels is increased by the addition of fiberglass insulation, the light transmittance is decreased. The panels can be used for walls and roofs of various shapes (e.g., barrel vaults).

have an R_{I-P} value of about 2, (R_{SI} = 0.35), but if translucent fiberglass is added, the R_{I-P} value can be raised as high as 10 (R_{SI} = 1.75). Unfortunately, as fiberglass is added to increase the thermal resistance, the transmittance of light decreases significantly. However, if silica aerogel is used instead of fiberglass, the panel can have both high thermal resistance and high solar transmittance (see Table 13.17). Even so, solar transmission always decreases with increasing thermal resistance, as shown in Figure 13.17e.

A delightful by-product of the translucency is the nighttime glow of the building walls and/or roof (Fig. 13.17f).

Well-insulated, high-transmission translucent panels can be used to solve the common top-lighting problem of too much light on sunny days and too little on cloudy days, while maintaining the proper winter/summer balance. Figure 13.17g shows a sawtooth clerestory facing south to collect more winter than summer sun, but the sloped roof is made of a translucent composite panel for collecting light from the sky on cloudy days. To prevent overheating

Table 13.17 Properties of Translucent Panels and Membranes

System	Thickness		R-Value		Solar Transmission %
	I-P (in.)	SI (mm)	I-P	SI	
Fiberglass membrane	1/16	2	1–2	0.18–0.35	5–10
Composite sandwich panel with fiberglass insulation*	2¾	70	2	0.35	50
	2¾		3	0.53	25
	2¾		5	0.88	15
	2¾		10	1.75	10
Composite sandwich panel with aerogel insulation	½	13	4	0.7	73
	1	25	8	1.4	53
	1¼	31	10	1.75	45
	2½	63	20	3.5	21

*Although the panel thickness is fixed, the amount of insulation in the cavity can be varied.

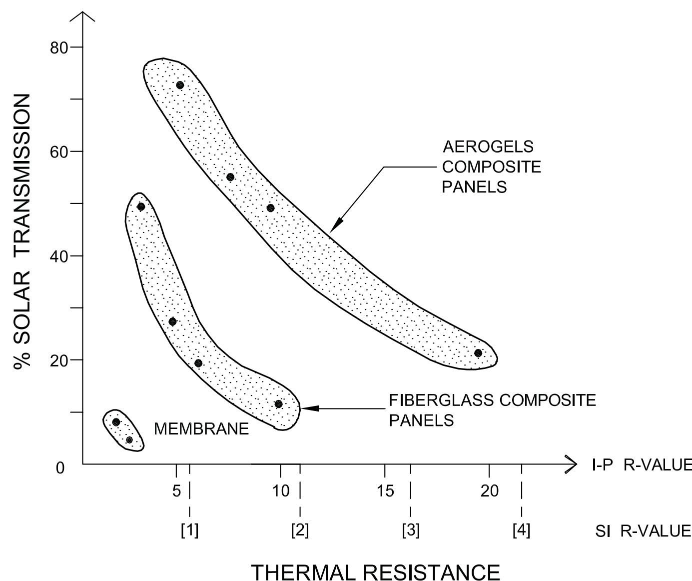


Figure 13.17e Like windows, translucent panels lose solar transmittance as their thermal resistance is increased. The points represent specific commercially available panels and membranes.



Figure 13.17f Translucent and insulated composite walls provide increased lighting by day and a spectacular luminescent architecture by night. (PA Technology, Princeton, NJ, by Richard Rogers, Kelbaugh & Lee Architects, photographs courtesy of Kalwall Corporation.)

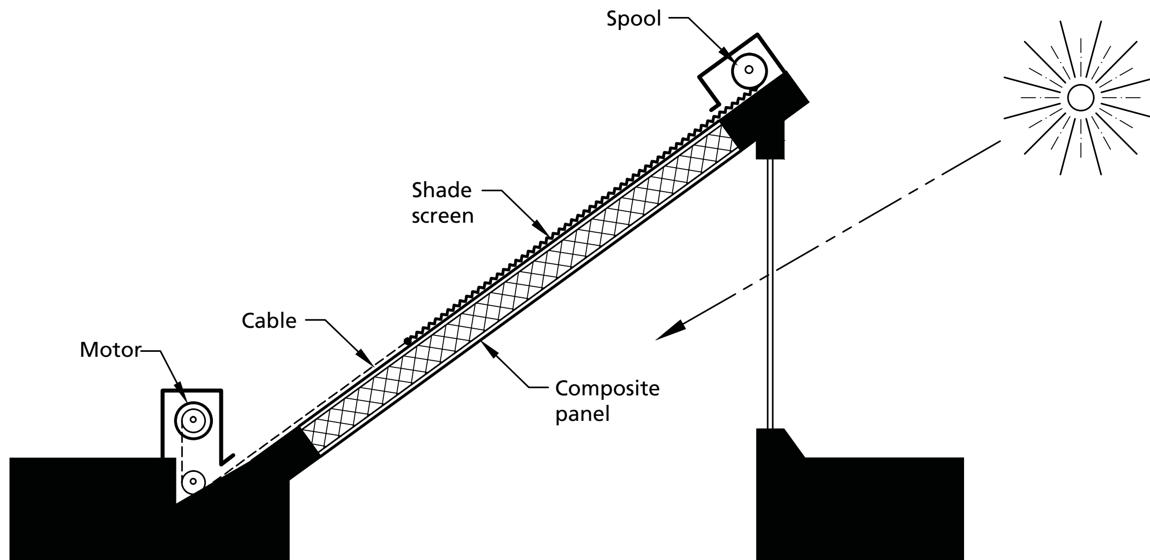


Figure 13.17g This clerestory and skylight combination collects the most sun in the winter. It also collects more daylight on cloudy and overcast days than conventional designs. The shade screen is withdrawn all winter and on cloudy overcast days in the summer. It is extended only on sunny days during the overheated period of the year.

on sunny days, an external shade screen is extended over the composite panels.

Use translucent glazing only for top lighting and high windows in high spaces!

13.18 ELECTRIC LIGHTING AS A SUPPLEMENT TO DAYLIGHTING

Even if a building is designed to be fully daylit, an electric lighting system is still required for stormy weather and nighttime use. A daylit building can save a significant amount of energy and electrical demand only if the electric lights are turned off when sufficient daylight is available. Although people can be relied upon to turn the lights on, few will turn the lights off when they are no longer necessary. This is understandable, because having both daylight and the electric lights on, thereby doubling the required illumination, is not visually objectionable and barely noticeable. The eye easily adapts to the higher illumination.

Consequently, automatic controls are necessary if daylighting is to save electricity. These controls consist of a photocell placed in the ceiling of the work area and a control panel of either the on/off or the dimming type. The on/off type is less expensive, while the dimming type saves more energy and is less disturbing to the users. To take advantage of these automatic controls, the lighting fixtures must be arranged to complement the available daylight. Figure 13.18a illustrates how the lighting gradient from part of the electric lighting can supplement the lighting gradient from daylighting. Figure 13.18b illustrates how the fixtures are arranged in rows or zones parallel to the windows so that any number of rows can be on or off as needed.

Fluorescent and LED lighting systems are the best choice for dimming and switching. Their lamps can be dimmed to about 15 percent of their light output without changes in color, and they can be turned on and off almost instantaneously. Since most high-intensity discharge sources (metal halide and high pressure sodium) have a long restrike time (five to ten minutes), they are not as suitable for switching strategies, but they can still be dimmed to about 50 percent of the normal light output.

The controls described above use sensors to control all the lighting fixtures in a zone simultaneously. A promising alternative is to have each fixture control itself. One system, called DaySwitch, uses an inexpensive electronic device in conjunction with the ballast of a fluorescent lighting fixture. With its own built-in sensor, it dims the fluorescent fixture as needed.

Not only do people leave electric lights on when there is more than enough daylight, they also leave them on when no one is in the room. Consequently, occupancy sensors are a very cost-effective solution to this problem. These sensors use either infrared radiation or ultrasonic vibrations to detect the presence of people. Combination occupancy and light-sensing devices are also available for daylit spaces.

For daylit spaces, a **vacancy sensor** may be a better choice than an occupancy sensor. An occupancy sensor turns the lights on when people enter and off when people leave, while a vacancy sensor only turns lights off when people leave. With such a sensor, the lights must be turned on manually, which people will happily do if it is too dark for them to see.

Daylighting should usually serve as the ambient part of a task/ambient lighting system. As described in the

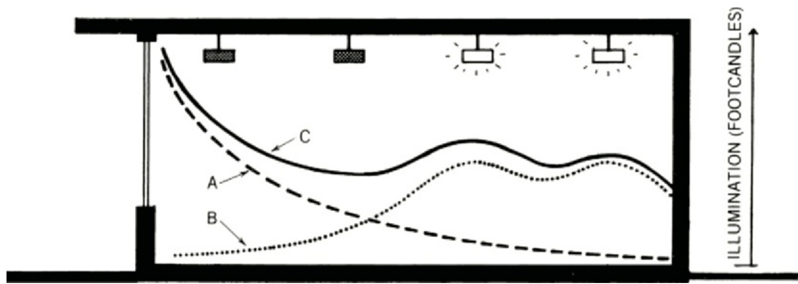


Figure 13.18a Daylighting (curve A) is supplemented by part of the electric lighting (curve B) to create a rather uniform light level (curve C).

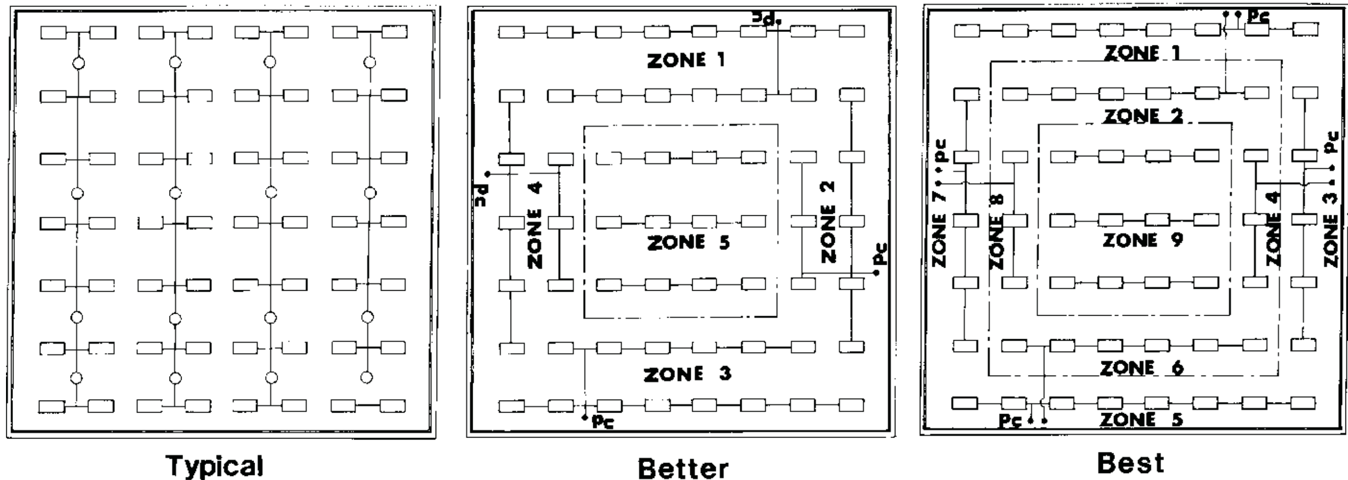


Figure 13.18b These reflected ceiling plans are for a building with windows on all four sides. Lighting zones should consist of fixtures in rows parallel to the windows on each orientation. "Pc" stands for photocell light sensor. (From *Daylighting: Performance and Design*, by Gregg D. Ander. © Gregg D. Ander, AIA., Southern California Edison.)

previous chapter, the ambient illumination is usually about one-third of the recommended task illumination. The user-controllable electric task lighting then gives people the control they need to get abundant high-quality light for their tasks.

Do not use electrical lighting without automatic controls to turn it off when daylighting is sufficient!

13.19 PHYSICAL MODELING

Simulation with physical models is by far the best tool for designing daylighting for a number of reasons:

1. Because of the physics of light, no error due to scale is introduced. Consequently, the model can reproduce exactly the conditions of the actual building. Photographs made of a real space and of an accurate model show identical lighting patterns (Figs. 13.19a and 13.19b).
2. No matter how complicated the design, a model can accurately predict the result.
3. Physical models illustrate both the qualitative and quantitative aspects of a lighting system (Figs. 13.19b–13.19d). This is especially significant since glare, veiling reflections, and brightness ratios are often more important than illumination levels.
4. Simple hand calculations or software can produce erroneous conclusions because of the very complex nature of daylighting, while sophisticated computer programs require significant time and experience to run. On the other hand, physical modeling requires little learning time and provides very reliable feedback and insight for both present and future projects.
5. Physical modeling is a familiar, popular, and appropriate medium for architectural design.
6. Physical models are very effective in communicating with the client as well as with the design team.
7. Although physical models are expensive to build and test, the resultant quality of design and improved skills of the designer make the investment worthwhile. Excellent results are obtainable from even crude study models as





Figure 13.19a The photo on the left is of an actual room, while the photo on the right is of a model of the same room. Both pictures were taken at the same time so that the available daylighting was identical. This side-by-side comparison shows that there is no inherent scaling error with light. (University of California, Davis Daylight Design Class—Design 198. Taught by Professor Konstantines Papamichael, Ph.D., Spring 2006.)

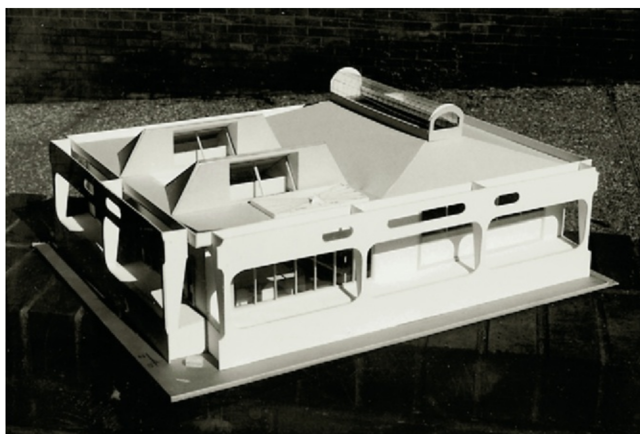


Figure 13.19b This daylighting model of a library was built as a school project at Auburn University, School of Architecture in Auburn, Alabama, by S. Etemadi, T. Peters, and C. Scaglione.



Figure 13.19d This photograph taken through a view-port shows the quality of the daylighting. Glare, excessive brightness ratios (puddles of sunlight), and the general lighting atmosphere are all easily and accurately determined.

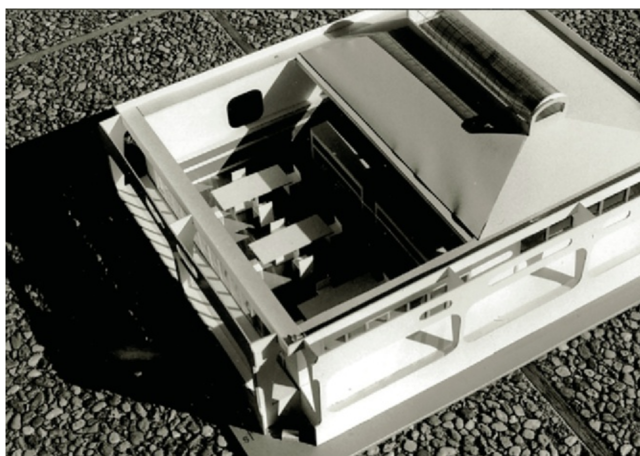


Figure 13.19c A part of the library's roof is lifted off to show the interior.

long as a few basic requirements are met.

8. Although excellent computer programs are now available, physical modeling is still the best way to learn the intricacies of daylighting. After daylighting design is well understood, computer modeling may be sufficient.

Important Considerations for Physical Modeling

1. Architectural elements that affect the light entering a space must be carefully modeled (e.g., the

size, depth, and location of windows, overhangs, mullions, and baffles). Use plastic film to simulate glazing, especially if tinted, reflective, or translucent glazing is being modeled.
2. Reflectance factors should be reasonably close to the desired finishes. The best solution is to use actual finishes whenever possible.
3. External objects that reflect or block light entering the windows should be included in the model test. Include adjacent walls, trees, ground finishes, and anything else that will reflect light into or prevent light from entering the model.
4. Opaque walls must be modeled with opaque materials. Note that foam-core boards are translucent unless covered with opaque paper. All joints must be sealed with opaque material, such as black cloth tape, black duct tape, or aluminum tape. Vinyl (electrical) tape is not useful because it does not stick well to cardboard.
5. Test the model under the appropriate sky conditions as described below.

Helpful Hints for Constructing Models

1. Use a scale of at least 1/2 in. = 1 ft (1:25) if possible, but for larger spaces or buildings, this scale can result in difficult models to build and transport. A scale of 3/8 in. = 1 ft (1:33) can still work quite well for large models. Model one space at a time.
2. Use modular construction so that alternative schemes can be easily tested. For example, the model might be constructed with interchangeable window walls.
3. Add view-ports on the sides and back for observing or photographing the model. Make the ports large enough for a camera lens to get an unobstructed view and for the photometer probe to pass through. A 2 in.^{2} (5 cm^2) hole is usually sufficient. To see what a person inside the modeled space would see, place the view-port at eye level (i.e., 5.5 ft. [1.7 m] to scale). Windows on the model cannot be used as view-ports because the observer's head would block a significant amount of light.
4. The quality of the model and the effort expended in its construction depend on the purpose of the model. If the model is not going to be used for presentations to clients, even a crude model is sufficient for determining illumination levels and gross glare problems.
5. Since furniture can have an important effect on the lighting, especially if it is dark, large, and extensive, it should be included. Simple blocks painted with colors of the appropriate reflectance factors can act as furniture in crude models.
6. A photometer (light meter) is a very valuable instrument for measuring the illumination (footcandles or lux) inside the model. The less expensive meters are usually quite adequate, but be sure to get a meter with a remote sensor (i.e., at the end of the wire).

Testing the Model

The climate of the site will determine which of the two critical sky conditions must be emphasized in testing the model. In most parts of the United States, a model must be tested under both an overcast sky and a clear sky with sun. The overcast sky determines whether minimum illumination levels will be met, and the clear sky with sun indicates possible problems with glare, excessive brightness ratios, and illumination levels around the year.

For consistent results, artificial skies are sometimes used for the model tests (Fig. 13.19e). Unfortunately, artificial skies are not available to most designers. The hemispherical artificial skies are more accurate but are very expensive and bulky to build. The rectilinear mirror skies are smaller and less expensive

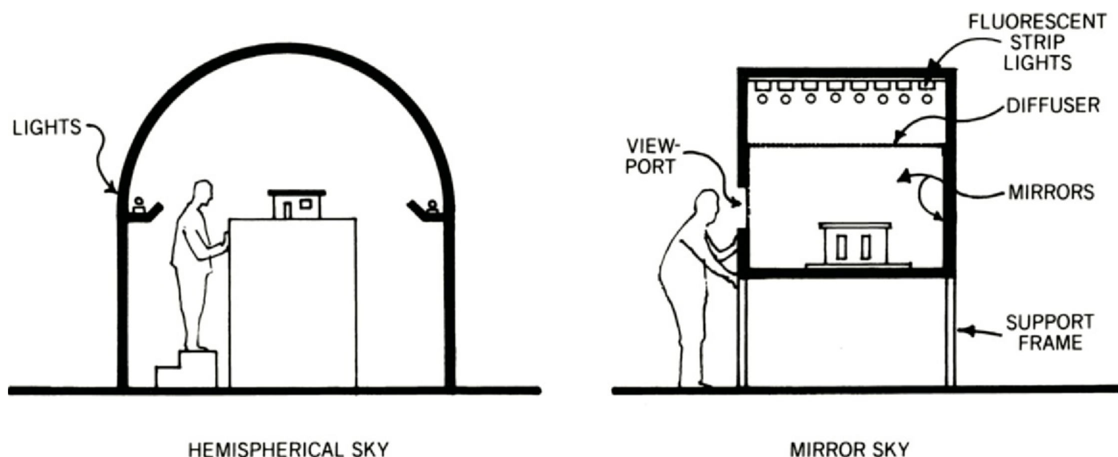


Figure 13.19e Artificial skies for testing models usually consist of either a white dome or a mirror-lined box.

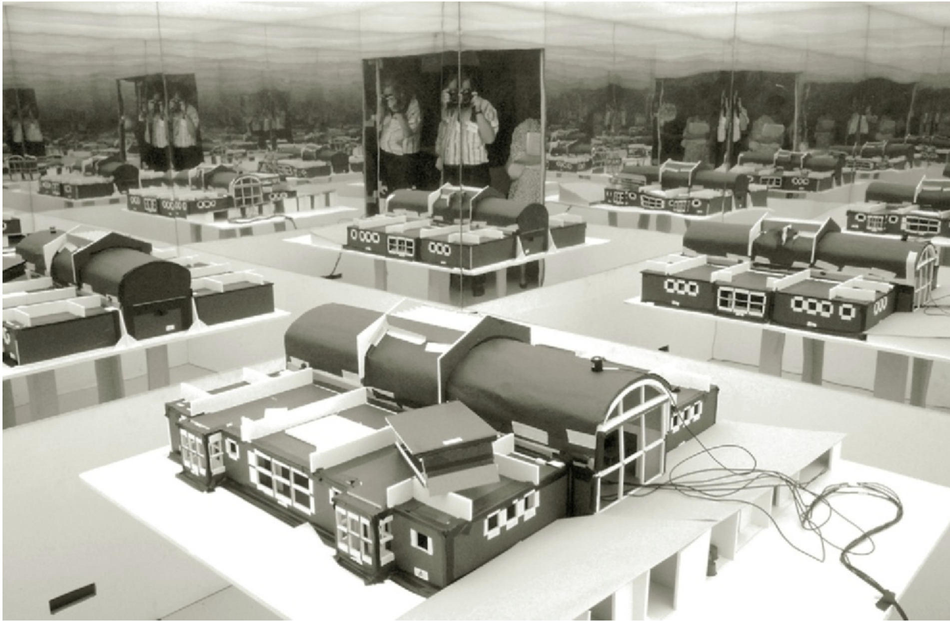


Figure 13.19f This view of the inside of a mirror sky shows how a standard overcast sky is created, but it also shows the confusing images that multiple mirrors create.

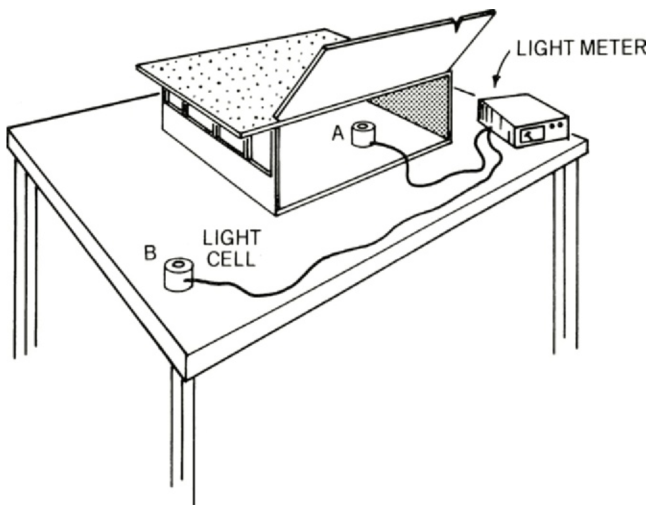


Figure 13.19g The daylight factor is determined by dividing the indoor illumination by the outdoor illumination. When the same cell is used for both measurements, the time between readings must be minimized.

but still quite rare (Fig. 13.19f). Most artificial skies simulate only standard overcast conditions, yet the consequences of direct sunlight are most critical. Thus, for a number of reasons, the real sky and sun are usually used to test daylighting models.

Avoid testing a model under partly cloudy conditions because the lighting will change too quickly to allow reliable observations. Although overcast and clear skies are quite consistent from minute to minute, they vary greatly from day to day. For this reason, all quantitative comparisons between alternative schemes should be based on the daylight factor and not on footcandles or lux. As mentioned before, the daylight factor is a relative factor determined by measuring the horizontal indoor and outdoor illumination levels at more or less the same time. Under overcast skies, the daylight factor remains constant even when the outdoor illumination changes. See Section 13.5 for a discussion of the daylight factor.

The human eye is the ideal tool for checking qualitative aspects of the design. The eye is also quite good at determining the adequacy of illumination levels. To get accurate results, look into the view-ports for several minutes to allow your eyes to adapt to the lower light levels inside the model.

Outdoor Model-Testing Procedure for Overcast Skies

1. Place the model in the correct orientation on a table at the actual site or at a site with similar sky access and ground reflectances. If neither of the above is possible, include the major site characteristics in the model to simulate the horizon profile (e.g., high buildings or trees) and test it on a roof or other clear site.
2. Place the photometer sensor at the various critical points inside the model to be tested. Usually, the critical points to check are the center of a room and 3 ft (1 m) from each corner. The top of the sensor should be about 30 in. (75 cm) to scale above the floor in the model (Point A in Figure 13.19g).
3. Measure the horizontal outdoor illumination level by moving the sensor to point B (Fig. 13.19g),



Figure 13.19h A tabletop heliodon is used to hold the daylighting model at various orientations and tilt angles as determined by the sundial mounted on the table. View-ports allow observation of the lighting without affecting the light collected by the windows.

then calculate the daylight factor (DF = A/B)

4. Use the view-ports on the sides and back of the model to check visually for glare, excessive-brightness ratios, and the general quality of the lighting. Use hands or a black cloth to prevent stray light from entering the view-port during observations. Take photographs for a permanent record.

Outdoor Model-Testing Procedure for Clear Skies

The procedure is basically the same as that for overcast skies except that the model must be tilted and rotated to simulate the range of sun angles throughout the day and year (Fig. 13.19h). At a minimum, the model should be tested for the conditions of June 21 at 8 A.M., noon, and 4 P.M. and December 21 at 9 A.M., noon, and 3 P.M. It is very important to test the model under varying sun angles to prevent potentially serious glare and sun puddle problems. One can best accomplish this procedure by means of a table-top heliodon and a sundial, as described in Appendix I. Use the directions given under "Alternative Mode of Use of the Heliodon."

Photographing the Model

Photographs greatly enhance the usefulness of physical models as design tools. Photographs of model interiors facilitate the careful analysis and comparison of various lighting schemes. Photographs of well-constructed models also make for effective presentations to clients. Remember, though, that the camera does not see the way the human eye does. Brightness ratios always appear worse in photos than they are in reality. The eye can also change focus as required, while the camera freezes one view. Either the near or the far image might be out of focus. Nevertheless, photography is a valuable adjunct to physical modeling. The following suggestions are for photographing the interiors of physical models.

1. Use wide-angle lenses for their large field of view as well the increased depth of field.
2. Depth of field can also be maximized by using a tripod, which will allow for slow shutter speeds and therefore small apertures.
3. Bracket each photograph by taking shots at least one-half exposure setting higher and one-half setting lower than what the camera meter says.
4. Keep the center of the lens at eye level of a standing scale figure in the model.
5. Do not allow light to leak into the model through the view port around the camera lens. Use a black cloth if necessary.

The best way to learn daylighting design is through physical modeling!

More Information on Physical Modeling

For more information on model building and testing, see *Simulating Daylight with Architectural Models*, edited by Marc Schiler.

13.20 GUIDELINES FOR DAYLIGHTING

1. General principles.
   a. Integrate daylighting design with the architecture.
   b. Integrate daylighting design with passive solar, shading, and electric lighting.
   c. Design the building as a lighting fixture (luminaire).
2. Use top lighting whenever possible.
   a. Use clerestories and avoid skylights.
   b. Face clerestories south if there is a significant heating load.
   c. Face clerestories north if the building has no heating load or a minor heating load.
   d. Use east and/or west clerestories only if south or north clerestories are impossible.
   e. Use louvers or baffles to diffuse light, to avoid glare, and to prevent puddles of sunlight.
3. For daylighting from windows:
   a. Design the form of the building to maximize the daylit areas. Use a long rectangle or an atrium.

b. Maximize south windows if winter heating is required.
c. Maximize north windows if winter heating is not required.
d. Avoid east and west windows. If they cannot be avoided, use as few as possible and keep them short (i.e., vertically challenged).
e. Use light shelves except on the north facade.
f. Use separate view and daylight windows. Have daylight windows high on the wall.
g. Use venetian blinds or shades for backup and flexibility.
h. Use open floor plans (avoid partitions) for maximum light penetration and views.
i. Use glass partitions to allow for borrowed daylight.
j. Use light colors on the exterior to reflect light into the windows and clerestories.
k. Use light colors on the interior to maximize light penetration, to diffuse the light, and to minimize glare.

4. For energy efficiency:
   a. Use windows with a low U-factor, which is the same as a high R-factor (see Section 3.17).
   b. Design to maximize the quantity of daylight in the winter and to harvest just enough in the summer.
   c. Redirect daylight farther indoors to increase the area illuminated.
   d. Design for quality daylight in regard to glare and brightness ratios to ensure occupant support for daylighting. Otherwise, the daylighting system will be sabotaged and the electric lighting will be on all of the time.
   e. Use automatic controls to turn off electric lighting when the daylighting is sufficient.

13.21 CONCLUSION

As Louis I. Kahn suggests at the beginning of this chapter, daylighting brings meaning and richness to architecture. People want and need natural light for psychological, physiological, and spiritual reasons. Although more complicated to design than electric lighting, daylighting has profound aesthetic consequences for both the interior and exterior of buildings. The various daylighting strategies, such as light shelves and clerestories, change the appearance of buildings. Daylighting allows architects to economically justify additional visual elements that enrich the design.

The environment is also enriched. With daylighting, fewer fossil energy sources need to be extracted from the earth and less carbon dioxide is dumped into the environment. Daylighting is an important strategy in the effort to reduce global warming. Thus, daylighting enriches life as well as architecture.

KEY IDEAS OF CHAPTER 13

1. Until the mid-twentieth century, all buildings were daylit.
2. Daylighting is still appropriate because:
   a. People need and enjoy the qualities of daylight.
   b. It saves energy for a sustainable future, and it can reduce electrical demand. It helps fight global warming.
3. Daylight is a very plentiful resource. On an overcast day, the illumination on the roof is about 30 times what is required indoors, and on a sunny day it is about 160 times greater (varies with latitude).
4. Daylighting designs should distribute light evenly throughout the space throughout the day.
5. For daylighting to succeed and be accepted by occupants, it must be of very high quality by minimizing glare, veiling reflections, and excessive brightness ratios.
6. South lighting is best because it is warm, plentiful, easy to control, and in tune with the seasons (maximum in winter and minimum in the summer).
7. North lighting is second best because it is constant and cool. However, it is not as plentiful or warm as south lighting.
8. Avoid east and west lighting if possible because of the glare from low sun angles and summer overheating.
9. Although all light turns into heat, electric light sources heat a building more than daylight.
10. In the summer, introduce only enough daylight to supply the required illumination levels; in winter, collect all the daylight possible (except in internally dominated buildings in mild climates).
11. Use spectrally selective glazing for cool daylighting.
12. Where winter heating is not desired, use spectrally selective glazing for cool daylight, even on the south facade.
13. Use top lighting whenever possible.
14. Use clerestories rather than skylights.
15. Use light shelves.
16. Use electric lighting as a supplement to daylighting.
17. Use physical models to help design high-quality daylighting.
18. Use photocell controls to automatically dim or turn off lights when sufficient daylight is present.

References

Baker, N., A. Fanchiotti, and K. Steemers, eds. *Daylighting in Architecture*. London: James & 2000 James, 1993.

IESNA Lighting Handbook, 10th ed.

Loftness, Vivian. "Improving Energy Efficiency in the U.S.: Technologies and Policies for 2010 to 2050," prepared for the PEW Center on Global Climate Change, 2004.

Moore, F. *Concepts and Practice of Architectural Daylighting*. New York: Van Nostrand Reinhold, 1985.

Willmert, T. "Prismatic Daylighting Systems, Once Commonly Used, Reemerge as a Promising Technology for the Future," *Architectural Record*, August 1999, pp. 177–179.

Resources

Further Reading

(See the Bibliography in the back of the book for full citations.)

Ander, G. D. *Daylighting Performance and Design*, 2nd ed.

Baird, G. *The Architectural Expression of Environmental Control Systems*.

Brown, G. Z., and M. DeKay. *Sun, Wind, and Light: Architectural Design Strategies*, 3rd ed.

Carmody, J., S. Selkowitz, and L. Heschong. *Residential Windows: A Guide to New Technologies and Energy Performance*, 3rd ed.

Carmody, J., S. Selkowitz, E. S. Lee, D. Arastem, and T. Willmert. *Windows Systems for High-Performance Buildings*.

Commission of the European Communities Directorate-General XII for Science Research and Development. *Daylighting in Architecture: A European Reference Book*.

Daniels, K. *The Technology of Ecological Building: Basic Principles and Measures, Examples, and Ideas*.

Egan, M. D. *Architectural Lighting*, 2nd ed., 2002.

Energy Design Resources. *Skylighting Guidelines*.

Evans, B. E. *Daylight in Architecture*.

Fitch, J. M., with W. Bobenhausen. *American Building: 2. The Environmental Forces That Shape It*.

Flynn, J. E., J. A. Kremers, A. W. Segil, G. Steffy. *Architectural Interior Systems: Lighting, Acoustics, Air-Conditioning*, 3rd ed.

Franta, G., K. Anstead, and G. D. Ander. *Glazing Design Handbook for Energy Efficiency*.

Futagawa, Y., ed. *Light and Space: Modern Architecture*.

Guzowski, M. *Daylighting for Sustainable Design*.

Hopkinson, R. G., P. Petherbridge, and J. Longmore. *Daylighting*.

Köster, H. *Dynamic Daylighting Architecture: Basics, Systems, Projects*. Basel, Switzerland: Birkhauser Publishers, 2004.

Kwok, A., and W. Grondzik. *The Green Studio Handbook: Environmental Strategies for Schematic Design*.

Lam, W. M. C. *Sunlighting as Formgiver for Architecture*.

Millet, M. S. *Light Revealing Architecture*.

Moore, F. *Concepts and Practice of Architectural Daylighting*.

Phillips, D. *Daylighting: Natural Light in Architecture*.

———. *Lighting Modern Buildings*.

Robbins, C. *Daylighting: Design and Analysis*.

Schiler, M. *Simplified Design of Building Lighting*.

———. *Simulating Daylighting with Architectural Models*.

Steffy, G. R. *Architectural Lighting Design*, 2nd ed.

———. *Time-Saver Standards for Architectural Lighting*.

Stein, B., J. S. Reynolds, W. T. Grondzik, and A. G. Kwok. *Mechanical and Electrical Equipment for Buildings*, 10th ed.

Organizations

(See Appendix K for full citations.)

California Collaborative for High Performance School (CHPS), www.chps.net

California Lighting Technology Center, www.cltc.ucdavis.edu

Heschong-Mahone Group, www.h-m-g.com

IESNA Illuminating Engineering Society of North America, www.iesna.org

International Association of Lighting Designer (IALD), www.iald.org

Lawrence Berkeley National Laboratory (LBNL), www.eande.lbl.gov

Lighting Design Lab, www.northwest-lighting.com

Lighting Research Center, Rensselaer Polytechnic Institute, www.lrc.rpi.edu

Web Sites

For more information on prismatic systems, see:

http://weekendstubble.blogspot.com/2008/05/seize-daylight.html

http://glassian.org/Prism/index.html

http://www.d-lite.org/dlite_system.php

CHAPTER 14

ELECTRIC LIGHTING

The greatest responsibility is to be good ancestors.
Dr. Jonas Salk

Light has always been recognized as one of the most powerful formgivers available to the designer. . . . Theoretically, the possibilities for imaginative lighting are limitless. And, theoretically, our ability to create great architecture should have increased in proportion to the availability of more, and more versatile, artificial [light] sources. Yet we have scarcely begun to scratch the surface of these "limitless" possibilities.
William M. C. Lam,
Perception and Lighting as Formgivers for Architecture, *1977*

14.1 HISTORY OF LIGHT SOURCES

Throughout most of human history, activities requiring good light were reserved for daylight hours. This was true because of the poor quality of the available light sources, and even more so because of the expense. Oil lamps (Fig. 14.1a) and candles, the main sources of light, were so expensive that even the rich did not use more than a few at a time. For the poor, the choice was often light or food since lamps burned cooking oil and most candles were made from animal fat (tallow). During the eighteenth and early nineteenth centuries, the whaling industry existed mainly for supplying oil and wax for lighting needs. An energy crisis developed due to the overhunting of sperm whales. Fortunately for both whales and lighting, kerosene, which is extracted from petroleum, replaced whale oil, and the petroleum age was born (Fig. 14.1b).

Coal gas was another important light source in the nineteenth century. At first, it was considered safe only for street lighting (Fig. 14.1c), but eventually it was accepted indoors as well. The light, however, was not much better than that from oil lamps until the invention of the mineral-impregnated mantle in the 1880s (Fig. 14.c and 14.1d), which greatly improved both the quality and quantity of gas light. Since gas lighting, even with the mantle, still caused many fires and generated much heat, and since the products of combustion were a dirty and serious health hazard, it was quickly replaced by electric lighting at the beginning of the twentieth century.

Thomas Edison did not invent the idea of the electric incandescent lamp, but he was one of the first to make it practical, around 1880. He also developed efficient electric generators and distribution systems without which the electric lamp was worthless. Although the



Figure 14.1a The history of the oil lamp is about as old as the history of humanity. The photo shows a Roman double-burner.

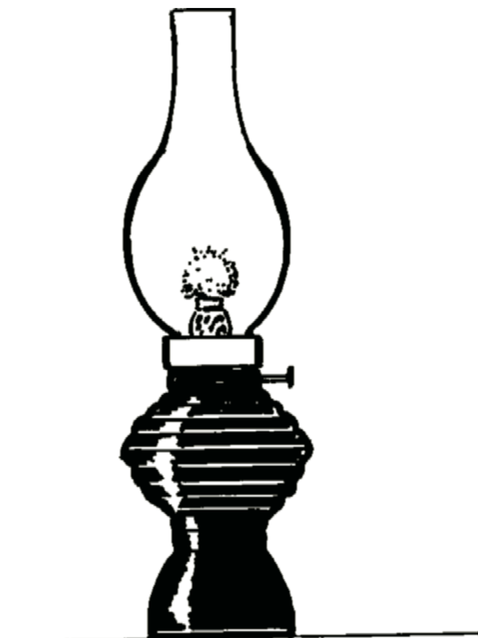


Figure 14.1b The kerosene lamp launched the petroleum age in the mid-nineteenth century.



Figure 14.1c The mantles can be seen in this two-burner streetlight in Mobile, Alabama. Lamplighters used to turn the gas on and light it in the evening and turn it off in the morning.

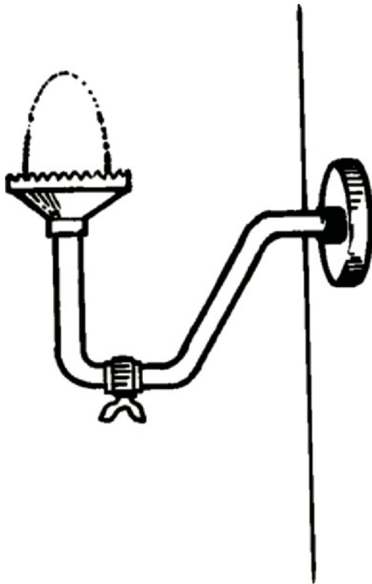


Figure 14.1d Not until the invention of the mantle did gas lamps significantly improve the quality of artificial lighting.

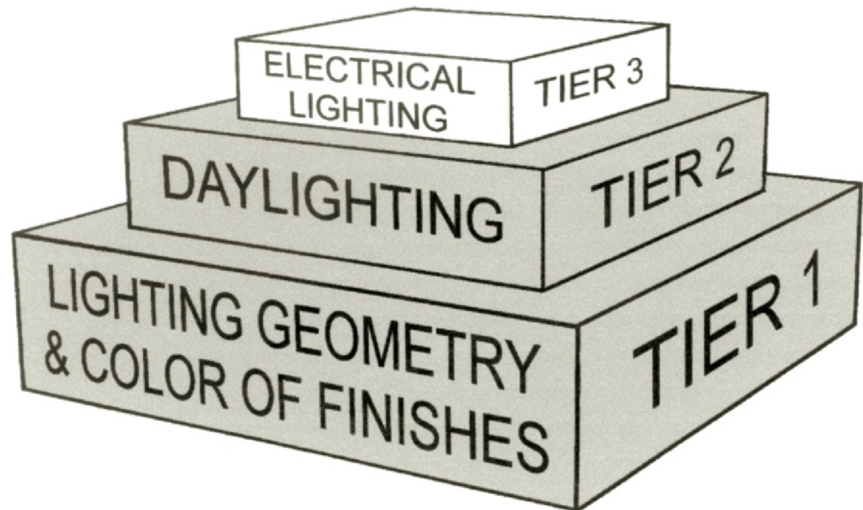


Figure 14.1e The best and most sustainable lighting design results when the three-tier design approach is applied, and this chapter covers tier three (electric lighting).

incandescent lamp was an excellent light source for general illumination compared to what was available before, the development of discharge and LED lamps has made the incandescent lamp obsolete. The first major new lamp was the fluorescent lamp, which was introduced in the late 1930s.

Until the invention of gas and electric lighting, streets and public buildings were largely abandoned after dark. Now many facilities, such as offices, factories, stores, and even outdoor sporting areas, are available twenty-four hours a day. It has been suggested that today's frontier is not space but nighttime.

As mentioned in the previous two chapters, electric lighting is part of the third tier of the three-tier design approach for sustainable lighting. The architect should make full use of geometry, color of finishes, and daylighting before the electric lighting system is designed (Fig. 14.1e).

14.2 LIGHT SOURCES

Figure 14.2a shows the primary sources of electric light for buildings. Figure 14.2b shows the relative efficiency of various light sources by giving the number of lumens emitted for each watt of electricity used. This specific ratio of **lumens per watt** is called **efficacy**. The figure clearly shows that although the modern incandescent lamp was once considered a good light source, it is inefficient when compared to what else is available. The efficacy of each lamp type is shown as a range because efficacy is a function of several factors including wattage. High-wattage lamps have greater efficacy than low-wattage lamps. For example, a 100-watt lamp gives off much more light than the combined effect of two 50-watt lamps. The spectral distribution also influences the efficacy of lamps. For example, warm white lamps have a lower efficacy than cool white lamps.

The theoretical maximum efficacy is where 100 percent of the electrical energy is converted into light. For monochromatic yellow-green light, this would be about 680 lumens/watt, while for white light it is only about 200 lumens/watt. This difference exists because the human eye is not equally sensitive to all colors. Since the eye is most sensitive to yellow-green light, a lamp of that color will have the highest efficacy. The eye is not very sensitive to such colors as red and blue, and any light containing these colors, such as white, will have a lower efficacy than yellow-green monochromatic light. Therefore, whenever color rendition is important, we must accept the lower efficacy of white light.

The modern incandescent lamp turns only about 7 percent of the electricity into light; the other 93 percent is immediately turned into heat (Fig. 14.2c). Although the fluorescent lamp is a great improvement, it still converts only about 28 percent of the electricity into light. Consequently, electric lighting, and especially incandescent lighting, not only uses large amounts of valuable electrical energy but also contributes greatly to the air-conditioning load of a building.

One way that building codes regulate lighting efficiency is by specifying the maximum number of watts permitted per square foot (watts per square meter) of floor area. See Table 14.2 for the efficiency requirements of various codes for offices.

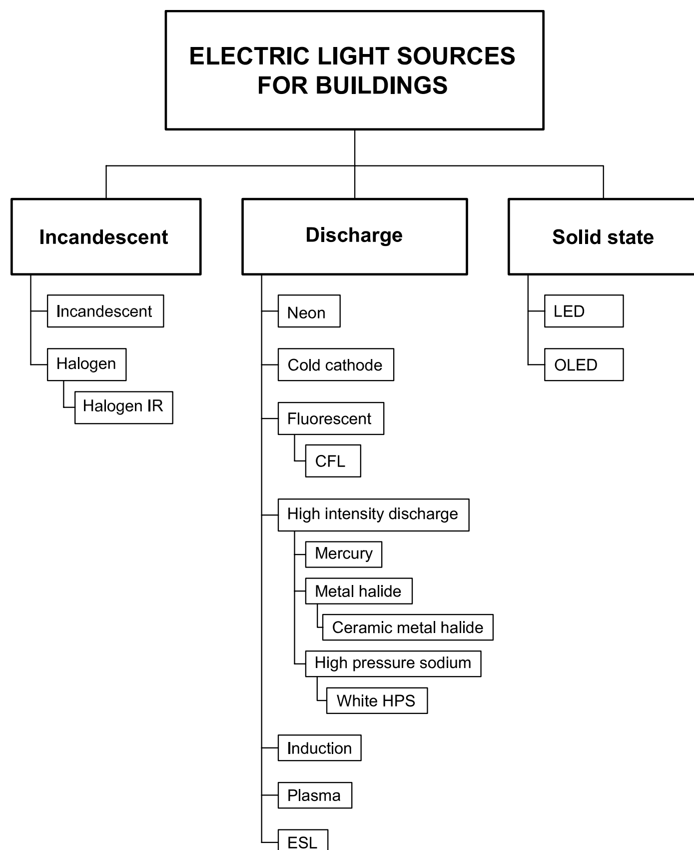


Figure 14.2a This chart shows the primary sources of electric lighting for buildings. At present, discharge lamps are the primary light source, but in the future they may well be replaced by the solid state sources. Abbreviations: LED (light-emitting diode), OLED (organic light-emitting diodes), CFL (compact fluorescent lamp), HPS (high pressure sodium), and ESL (electron stimulated luminescence).

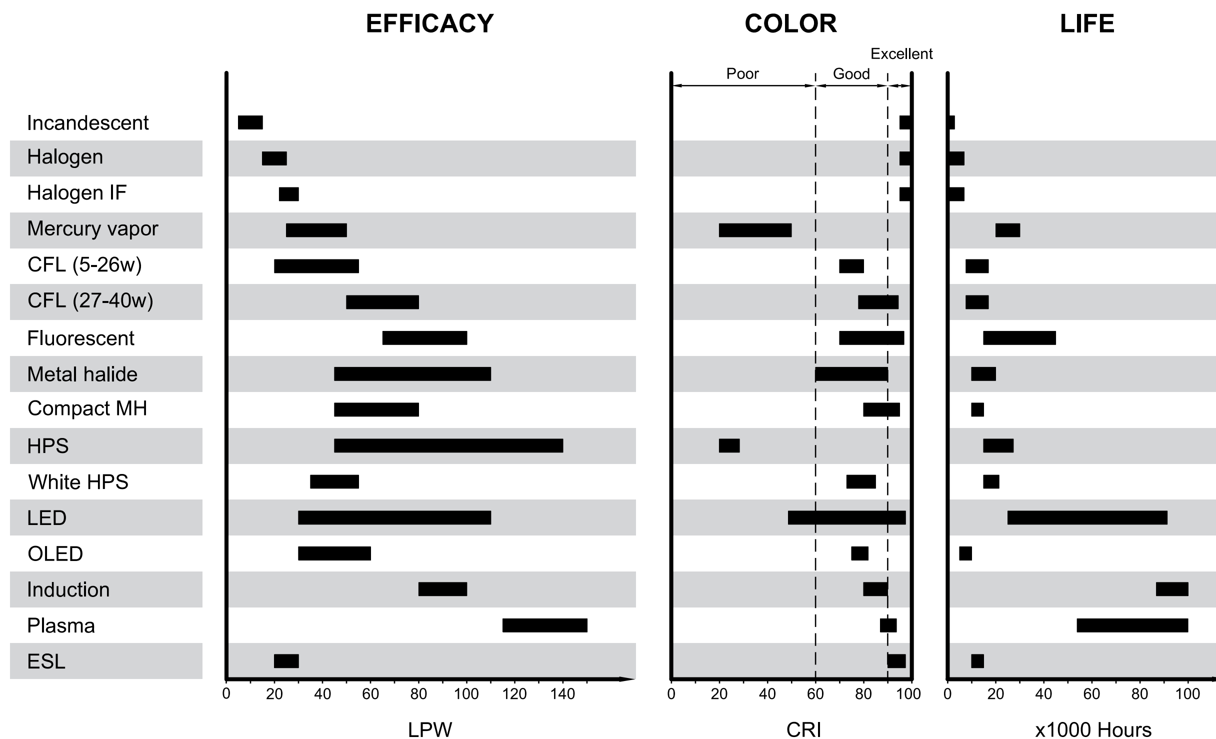


Figure 14.2b In choosing a lamp, the three major characteristics are efficacy (lumens per watt), color rendering (CRI), and the life of the lamp. To make comparisons easier, all three characteristics are shown side by side.

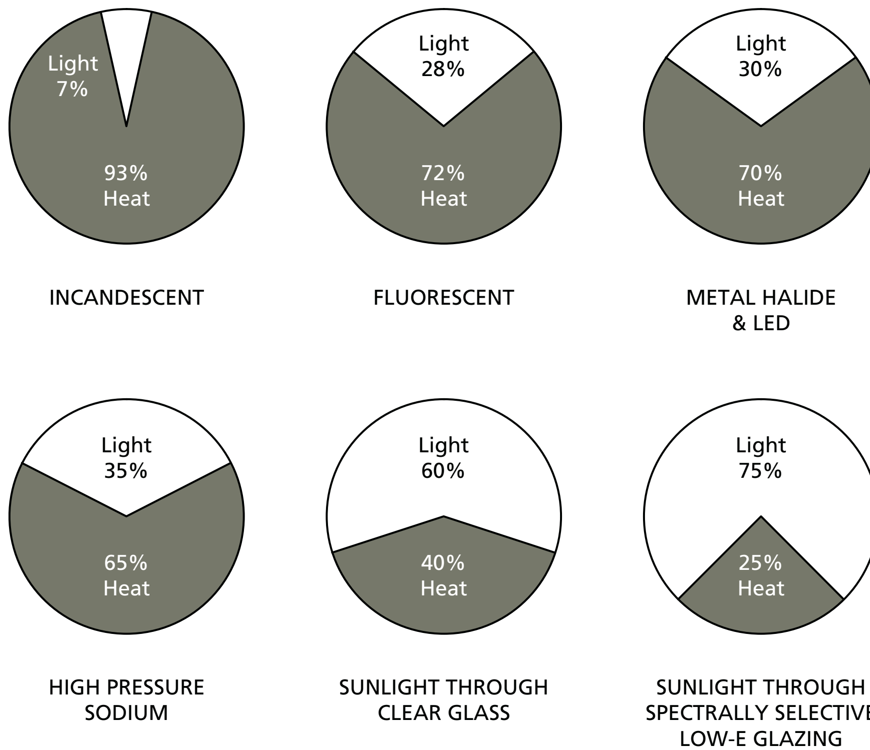


Figure 14.2c These pie charts show how much of the electrical energy is converted into light and how much is converted directly into heat. Clearly, the incandescent lamp is a very hot and inefficient light source since only 7 percent of the electricity is converted into light. It is important to note that daylight is the coolest light source only if the quantity that is brought into the building is carefully controlled.

Table 14.2 Maximum Lighting Power Density for an Office

w/ft^2	w/m^2	Code
5	47	Typical before energy codes
3	22	ASHRAE 90.1-1999
1	9.3	ASHRAE 90.1-2004
0.9	8.4	ASHRAE 90.1 2010
0.8	7.4	LEED
0.45	4.2	Possible during the day if daylighting is used

As discussed in the previous chapter, daylighting has a higher efficacy than any white electric light source, and it is free. Thus, electric lighting should be supplemental to daylight whenever possible. Electric light sources will now be discussed in ascending order of efficacy.

14.3 INCANDESCENT AND HALOGEN LAMPS

Although incandescent lamps are obsolete for general illumination, they are still used for a number of special applications. Since they are good at creating sparkle, they remain popular in some decorative lighting fixtures such as chandeliers. Although their first cost is low, their operating cost is very high in terms of both money and the environment. Several countries, including Korea, already prohibit the sale of most incandescent lamps, and many others, such as Australia, Canada, the European Union, and the United States, are phasing them out.

In an incandescent lamp, light is emitted by electrically heating a tungsten filament until it is reddish-white-hot (Fig. 14.3a). By increasing the current, the filament gets hotter and the light gets whiter (higher color temperature). Unfortunately, a hotter filament also burns out faster. Thus, the manufacturers build their incandescent lamps with an optimum design, balancing the life of the lamp and the amount of light emitted. The life of a typical incandescent lamp is only about 1000 hours.

Incandescent lamps wear out as the tungsten filament evaporates and condenses on the inside of the bulb, which causes the darkening of the glass. Eventually, as the filament gets thinner, it breaks. However, this evaporation of the filament can be reduced by adding halogen elements to the inert gases inside the lamp. These types of incandescent lamps can, therefore, be operated at higher temperatures without shortening lamp life excessively. This variation of the incandescent lamp is known as the **tungsten halogen** or **quartz iodine lamp** (Fig. 14.3b). Because of their intense light and small size, they are very popular as automobile headlamps, projector lamps, and spotlights for accent lighting. Halogen lamps have a slightly better efficacy than incandescent lamps, and a new version called the Halogen IR (infrared) is even better. However, LEDs are significantly better and will likely displace many halogen lamps in the near future.

One of the main advantages of halogen lamps is the optical control that is possible. A point source of light at the focal point of a parabolic reflector will produce a beam of parallel light (Fig. 14.3c). Although



Figure 14.3a The tungsten filaments of incandescent lamps are frequently coils of coils to concentrate the light source. (Courtesy of Osram Sylvania.)

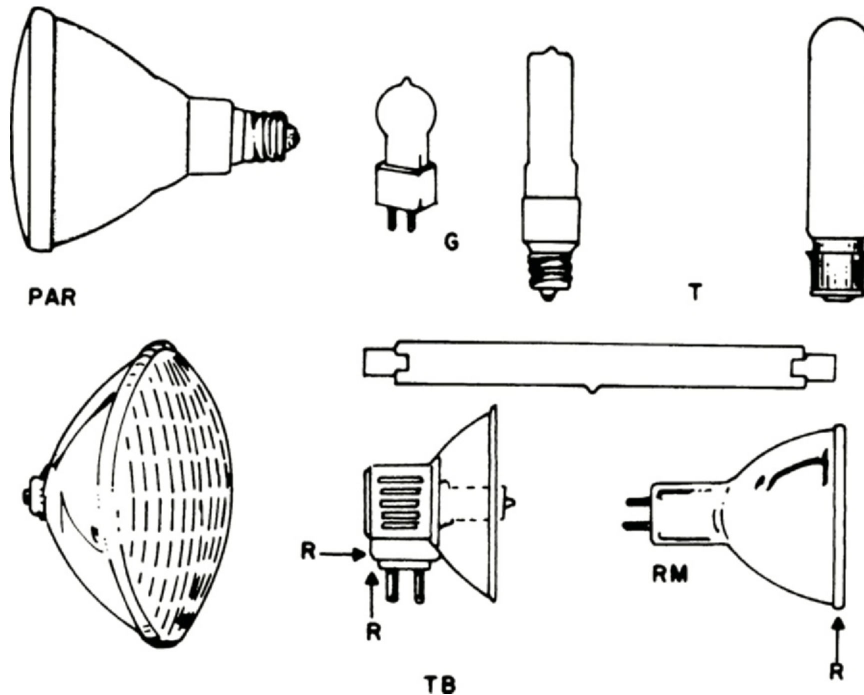


Figure 14.3b Common shapes of tungsten halogen lamps. (Courtesy of Osram Sylvania.)

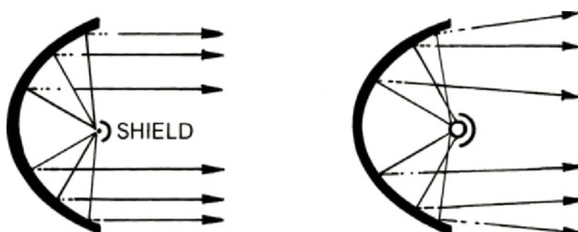


Figure 14.3c Parabolic reflectors will reflect light as a parallel beam if a point source is located at the focal point. Since all real sources are larger than a point, lamps cannot generate completely parallel beams of light.

there is no point source of light available, halogen lamps come closer than most other types of lamps. A tightly wound coil of a coil, as shown in Figure 14.3a, when placed at the focal point of a parabolic reflector, will create a narrow but not parallel beam of light.

Low-voltage (usually 12-volt) lamps have smaller filaments than 120-volt lamps and are, therefore, more of a point light source than regular lamps. They can yield beams as narrow as 5°, while regular 120-volt or higher lamps produce light beams 20° or wider (Fig. 14.3d). This makes low-voltage lamps very appropriate for accent lighting. They can save energy as well because, with the narrow beam, more light is on target and less is spilled on adjacent areas.

Most of the time, the beam spread of reflector lamps is described in words such as flood, spot, or narrow spot. Although beam spread can also be described in degrees, reflector lamps do not create beams with sharp cutoffs. Instead the light is strongest at the center (highest candlepower) and then gradually diminishes from there. Since there is no distinctive beam spread to measure, the beam angle is defined by the angle where the candlepower is at least 50 percent of the maximum (Fig. 14.3e).

The color-rendering quality of incandescent lamps is generally considered to be very good. Like daylight, the incandescent lamp emits a continuous spectrum, but unlike daylight, the color spectrum is dominated by the reds and oranges (Colorplate 9). The warm colors, including skin tones, are, therefore, complemented.

Because of the above-mentioned reasons of sparkle, beam control, and very good color rendition, a few incandescent and especially halogen lamps will continue to find specialty applications. Halogen lamps can be appropriate for accent lighting of small areas or objects, such as retail displays, sculpture, and paintings. Halogen lamps are especially appropriate when sparkle and specular

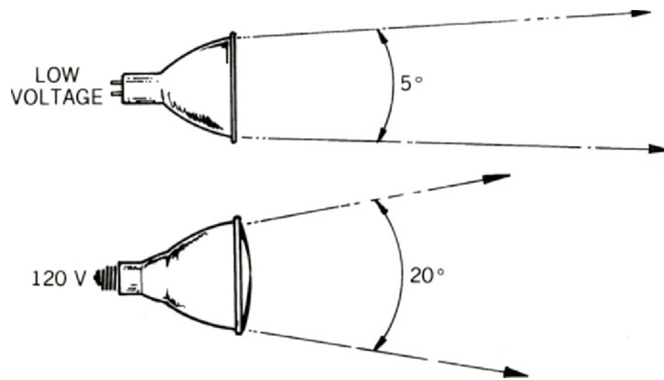


Figure 14.3d Low-voltage lamps can generate beams of light narrower than is possible with regular line voltage (120, 210, etc. volts) lamps.

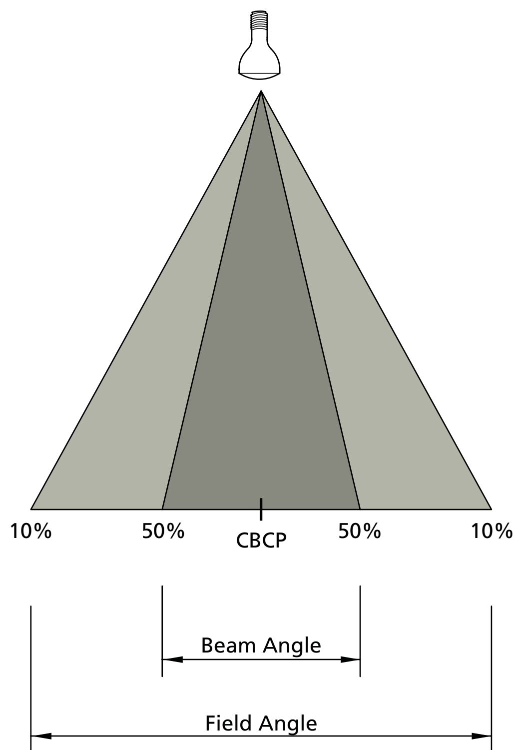


Figure 14.3e The beam spread of reflector lamps can be defined by the candlepower (candela) distribution. The beam angle is defined as that portion of the beam that has an intensity of at least 50 percent of the maximum intensity called the center beam candlepower (CBCP). Similarly, the field angle is defined as that portion of the beam that has an intensity of at least 10 percent of the CBCP.

reflectances are desired in the display of glassware, silverware, or jewelry. However, LED lamps are increasingly replacing halogen lamps.

The low efficacy of incandescent lamps makes such applications extremely energy wasteful and very expensive. Since their use also increases the cooling load on a building, it is appropriate to include part of the cost of the large air-conditioning equipment and the additional cost of operating the cooling equipment as part of the cost of the inefficient lighting. It is, therefore, clear that incandescent lamps should be used as little as possible and halogen lamps should be used sparingly.

14.4 DISCHARGE LAMPS

A major improvement in electric lighting came first with the development of the fluorescent lamp and then again with the development of high-intensity discharge lamps (mercury, metal halide, high pressure sodium). All of these lamps are based on a phenomenon known as **discharge**, in which an ionized gas rather than a glowing hot solid tungsten filament emits the light.

All discharge lamps require an extra device known as a **ballast** (Fig. 14.4), which first ignites the lamp with a high voltage and then limits the electric current to the proper operating level. Traditional ballasts that were made of copper coils are being replaced by electronic ballasts, which are more efficient and less noisy. The electronic ballasts also eliminate the problem inherent with magnetic ballasts producing 120 flashes per second, which disturbs some sensitive people.

The long life and high efficacy of the discharge lamps are more than enough to offset the extra cost of the ballast and the higher cost of each lamp when compared to incandescent lamps.

Although discharge lamps are much better for sustainability than incandescent lamps, some have the important liability of using the toxic element mercury. Lamp manufacturers are redesigning discharge lamps to use less mercury, but when the lamps are thrown away, the mercury enters the environment. One of the potential benefits of LEDs is that they use no mercury.

Since the various groups of discharge lamps differ from one other significantly, each group will be discussed separately.

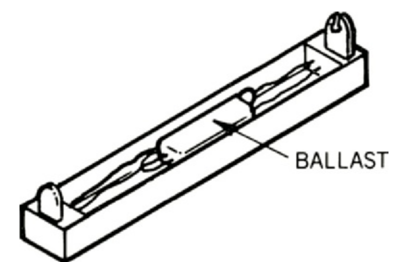


Figure 14.4 All discharge lamps require a ballast first to start the lamp and then to maintain the proper operating current.

14.5 FLUORESCENT LAMPS

Although the fluorescent lamp was first introduced in the 1930s, it is still one of the best light sources. It is available in a wide variety of sizes, colors, wattages, and shapes (Fig. 14.5a). Because of the concern with energy, **compact fluorescent lamps (CFL)** have been developed that can directly replace the much less efficient incandescent lamp (Fig. 14.5b). The recently developed **amalgam CFL** is more widely appropriate because it is much less sensitive to the ambient temperature. Because of global warming, it is imperative to minimize the use of incandescent lamps, and CFLs make that easy and even cost-effective.

In the fluorescent lamp, the radiation is emitted from a low-pressure mercury vapor that is ionized. Since much of the radiation is in the ultraviolet part of the spectrum, the inside surface of the glass tube is coated with phosphors to convert that invisible radiation into light (Fig. 14.5c). By using different kinds of phosphors, fluorescent lamps can be designed to emit various types of white light. For example, warm white lamps emit more energy in the red end of the spectrum, while cool white lamps emit more energy in the blue end of the spectrum (Colorplates 10 and 11). Specially formulated fluorescent lamps are available that give excellent color rendition.

Because the light is emitted from the surface of the glass bulb rather than from a point-like source, fluorescent lamps are not good for beam control. Although compact fluorescent lamps and the new slender linear lamps like the T5 (Fig. 14.5d) allow some beam control, they are best used for diffused area lighting. Other lamps, such as LEDs, are far superior when light needs to be carefully directed.

Long lamp life is another great virtue of the fluorescent lamp, but frequent starting cycles decrease the life of the lamp slightly. It was once considered prudent to leave lamps on to maximize their life, but the high cost of energy and the need to protect the environment make it proper to turn lights off when they are not required. The life of fluorescent lamps varies greatly by type, but some of the best lamps can now last for 46,000 hours. See Figure 14.2b

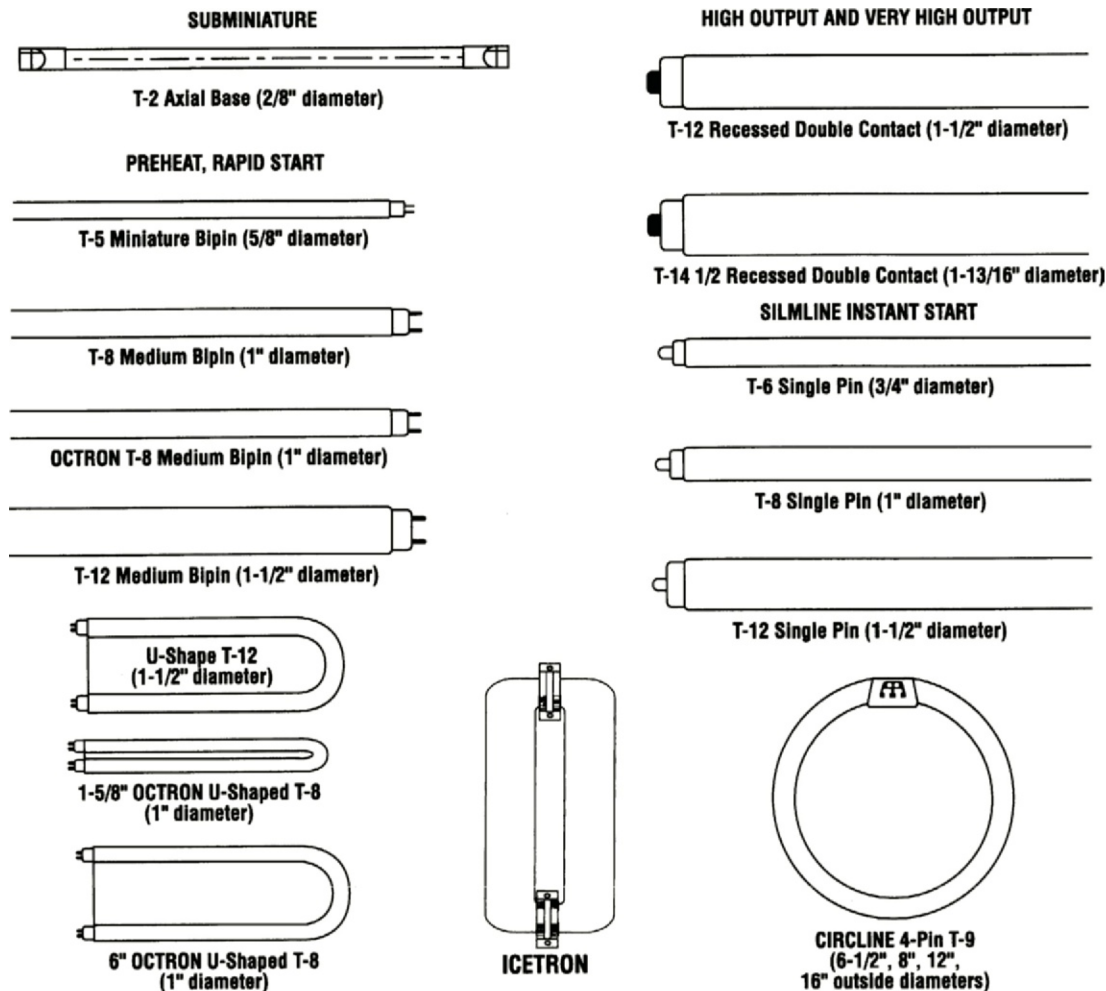


Figure 14.5a Common shapes of fluorescent lamps. (Courtesy of Osram Sylvania.)

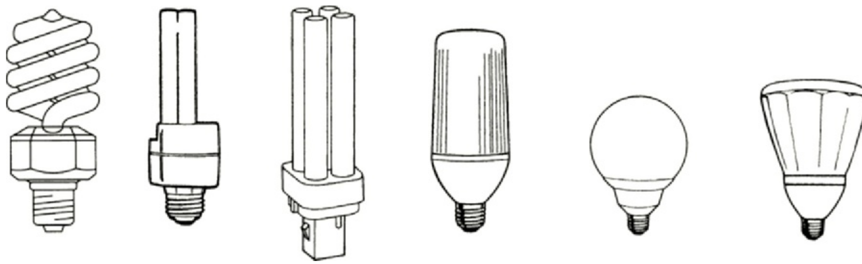


Figure 14.5b Compact fluorescent lamps (CFLs) are widely used around the world as replacements for incandescent lamps because of their high efficacy, warm color, and small size. The spiral shape is a result of the goal to get the most light out of the smallest-size fluorescent lamp. (Courtesy of Osram Sylvania and Duro-Test Lighting for the spiral lamp.)

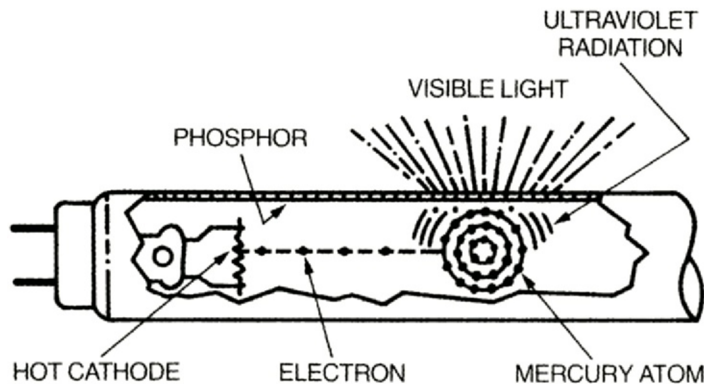


Figure 14.5c The basic features of a fluorescent lamp are shown. The ultraviolet radiation is converted into visible light by the phosphor coating on the inside of the glass tube. (Courtesy of GTE Products Corporation, Sylvania Lighting Center.)

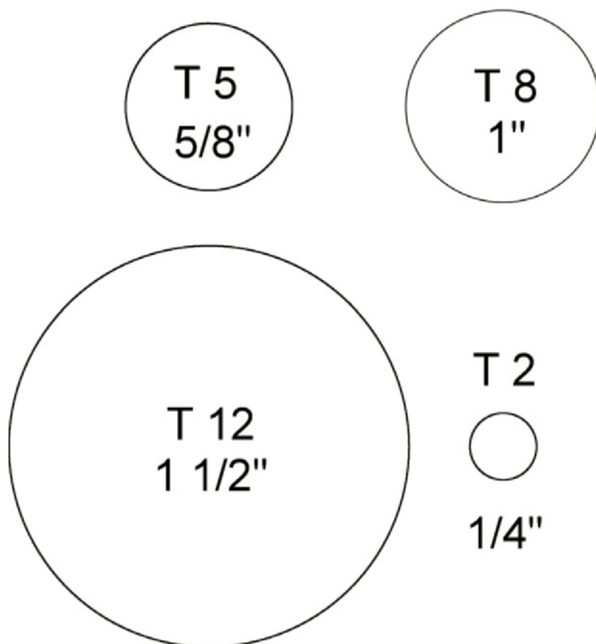


Figure 14.5d In standard fluorescent lamp designation, the T stands for "tubular" and the number after the T stands for the diameter in one-eighths of an inch. Although the T12 was the traditional size for decades, it is now obsolete in new fixtures. The T8 and T5 are now considered the standard sizes. The T5 is available in up to 5 ft (1.5 m) lengths, while the longest T2 is only 20 in. (0.5 m) long.

again for the expected life of various types of lamps.

Most fluorescent lamp ballasts are of the instant start kind, but rapid start ballasts are also used. However, a new ballast called programmed start has many advantages and is likely to become the dominant ballast in the future.

Neon Lamps

Neon lamps are close relatives of fluorescent lamps. These lamps use such gases as neon, which gives off red light, and argon, which gives off blue light. Through the use of different combinations of gases, colored glass, and phosphors, a large variety of rich, colored light sources is possible.

The main advantage of these lamps is that they can be custom-made to almost any desired shape. Neon, which uses about 0.5 in. (13 mm) diameter glass tubes, can be bent into very complex shapes. Neon lamps have long lives of about 25,000 hours. Neon is not suitable for area lighting because the light output is only one-sixth of that of an equally long fluorescent lamp. Rather, it is appropriate for applications that require special colors and shapes. These lamps are most suitable when the shape of the lamp is closely integrated with the form of the architecture (Fig. 14.5e) or when the shape of the lamp is itself the design element. However, LEDs, discussed below, are replacing neon in many applications.

Cold-Cathode Lamps

Cold-cathode lighting fits somewhere between fluorescent and neon lighting. Like fluorescent lighting, cold-cathode lighting uses phosphors to produce mainly white light, but it has a much lower efficacy than fluorescent lighting. Like neon, it is custom-made for a particular project, and like neon, it is for decorative rather than functional purposes (Fig. 14.5f).



Figure 14.5e Neon lights help define the entranceway into this office building on John Street in New York City.



Figure 14.5f Cold-cathode tubes are used for both form generation and illumination in the Town Center, Boca Raton, Florida. (Courtesy of National Cathode Corporation.)

14.6 HIGH INTENSITY DISCHARGE LAMPS (MERCURY, METAL HALIDE, AND HIGH PRESSURE SODIUM)

High intensity discharge (HID) lamps are very efficient light sources that in size and shape are more like incandescent than fluorescent lamps (Fig. 14.6a), but like all discharge lamps, they need a ballast to work. In all of the high intensity discharge lamps, the light is emitted from a small arc tube located inside a protective outer bulb (Fig. 14.6b). The relatively small size of this arc tube permits some optical control similar to that possible with a point source (see Fig. 14.3c). When increased color rendition is desired, metal halides are added to the mercury in the arc tube or phosphors are added to the inside of the outer bulb. However, the addition of phosphors greatly increases the size of the source, and some optical control is lost.

High intensity discharge lamps have two other important characteristics in common. They all require a few minutes to reach maximum light output, and they will not restrike immediately when there is a temporary voltage interruption. The lamps must cool for about five minutes before the arc can restrike. However, special instant-restrike lamps are available to prevent people from being left in the dark. If such lamps are not used, then a supplementary light source, such as fluorescent lamps, must be part of the design.

Mercury Lamps

Besides having lower efficacy than other discharge lamps, mercury lamps have poor color rendition. They produce a very cool light, rich in blue and green and deficient in the red and orange parts of the spectrum. Because of their blue-green light, mercury lamps are appropriate in landscape lighting, but otherwise they are considered obsolete.

Metal Halide Lamps

The white light that metal halide lamps emit is moderately cool, but there is enough energy in each part of the spectrum to give very good color rendition (Colorplate 12). Metal halide lamps are appropriate for stores, offices, schools, industrial plants, and outdoors where color rendition is important. These lamps are some of the best sources of light today because they combine in one lamp many desirable characteristics: high efficacy (50–110 lumens/watt), long life (20,000 hours), very good color rendition (CRI of 90+), and relatively small size for optical control. One of the important improvements in metal

Figure 14.6a The common shapes of high intensity discharge (HID) lamps. (Courtesy of Philips Lighting.)

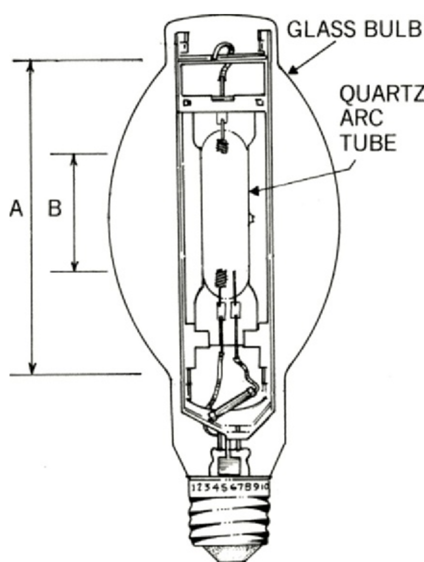


Figure 14.6b High intensity discharge (HID) lamps generate the light in the arc tube. This relatively small source (dimension B) allows a fair amount of optical control. When a phosphor coating on the bulb is used, however, the light source is much larger (dimension A) and beam control becomes difficult. (Courtesy of Osram Sylvania.)

halide lamps was the switch from the older probe-start to pulse-start ballasts.

Ceramic Metal Halide

Ceramic metal halide (CMH) lamps are different enough from other metal halide lamps to require a separate discussion. Because of their very good color rendition and small size, they can replace halogen lamps. Since CMH lamps last about four times longer and have about four times the efficacy of halogen lamps, they are superior to halogen lamps in many cases (see Colorplate 13).

High Pressure Sodium Lamps

When high efficacy (60–140 lumens/watt) and long life are of prime importance, the high pressure sodium

(HPS) lamp group is usually the design choice. Although the color rendition of HPS lamps is poor, some people find the warm golden-white light acceptable when color rendition is not important. Most of the emitted energy is in the yellow and orange parts of the spectrum (Color Plate 14).

HPS lighting is most appropriate for outdoor applications, such as lighting for streets, parking areas, sports areas, and building floodlighting. Research has shown, however, that for low-light peripheral vision (e.g., to see a deer at the side of the road or a mugger at the edge of a parking lot), white sources such as metal halide lamps far outperform poor color sources such as HPS lamps. Indoor spaces where color rendition is not important can also make use of the lamps' high efficacy. HPS lighting is quite appropriate for many industrial and warehouse spaces. The "white HPS" is a related but quite different lamp, which produces light that has very good color rendition. Unfortunately, its efficacy is much lower.

Because of improvements in metal halide lamps, it is now possible to get both high efficacy and good color rendition. Thus, many designers now specify metal halide where previously they would have specified HPS lamps.

A low pressure sodium lamp group also exists. Although it has the highest efficacy of any lamp group (130–180 lumens/watt), its monochromatic yellow light is unacceptable in most applications (see Colorplate 15).

Induction Lamp

The induction lamp is also known as the electrodeless fluorescent lamp, and its main virtue is its extremely long life of 100,000 hours. Although it has very good color rendition and efficacy, its high cost makes it appropriate only where lamp replacement is extremely difficult.

Plasma Lamp

Similar to a microwave oven, the gas inside a plasma lamp is heated by radio frequency energy hot enough to ionize the gas into a plasma. Plasma lamps make good replacements for high intensity discharge lamps because of their excellent color rendition, very high efficacy, very long life, and very good optical control. Small fixture size and great optical control are possible because of the lamp's small size.

Electron Stimulated Luminescence (ESL)

Similar to old-style TVs, electrons are emitted to strike a phosphor (fluorescent material), which then emits light. Because of their excellent color rendition (CRI about 95), fair efficacy (about 30 lpw), and relatively long life (about 11,000 hours) they can be a replacement for incandescent reflector lamps.

14.7 SOLID STATE LIGHTING

Solid state lighting (**SSL**) uses the same technology as the computer industry. SSL is extremely resistant to physical abuse and is also very long-lasting. It is improving very rapidly, and it has the potential to become the ideal light source, with 200 lumens per watt for white light. The most fully developed type of SSL lamp is the **light emitting diode (LED)**, while the organic light emitting diode (OLED) is only now coming on the market.

An LED is like a PV (solar) cell operating backward. Instead of light generating electricity, electricity generates light. Because the light is generated at a specific wavelength (color), LEDs are great for producing pure colored light that is appropriate for decorative or communication purposes such as traffic lights and building decoration.

However, generating white light is more complicated and expensive. The most common method is to use a blue LED to illuminate phosphors that then emit white light. The other method is to use the RGB method, which is also used in TVs and computer monitors. When the light from a set of red, green, and blue LEDs is combined, any color, including white, can be produced merely by adjusting the strength of each color.

Another intrinsic property of LEDs is that they are essentially a point source with the light emitted in one direction (Fig. 14.7a). This characteristic makes them ideal sources for applications where spot or narrow beams are required. They are, therefore, excellent replacements for all incandescent reflector lamps and CFLs used for downlights. This high level of directional control allows the design of luminaires that minimize the waste from spilled light, glare, and light trespass, which is important in outdoor lighting. However, this highly directional lighting is a liability where diffused area lighting is desired. In such cases, other light sources such as fluorescent lamps may be the best option, at least for now.

Although LEDs do not need a ballast, they do need a power supply, which adds both cost and additional energy loss (14.7b). Unlike all of the other light sources, LEDs produce very little heat in the form of infrared radiation. Thus, they are very good for illuminating chocolate and refrigerated foods. However, they do produce large amounts of sensible heat for which a heat sink is needed. LEDs are usually mounted on metal blocks that conduct the heat away from the diodes into the air behind the lamp (Fig. 14.7c). It is extremely important to maintain the proper chip temperature.

Unlike most other light sources that are reaching their theoretical limit, LEDs have the promise of much greater efficacy along with excellent color rendition and long life. LEDs are a good complement to their close relatives, the organic light emitting diodes described next.

Organic light emitting diodes (OLEDs) are area sources that come in very thin flexible sheets, which emit a diffuse light. They are still at their early stage of development, with just a few lamps now

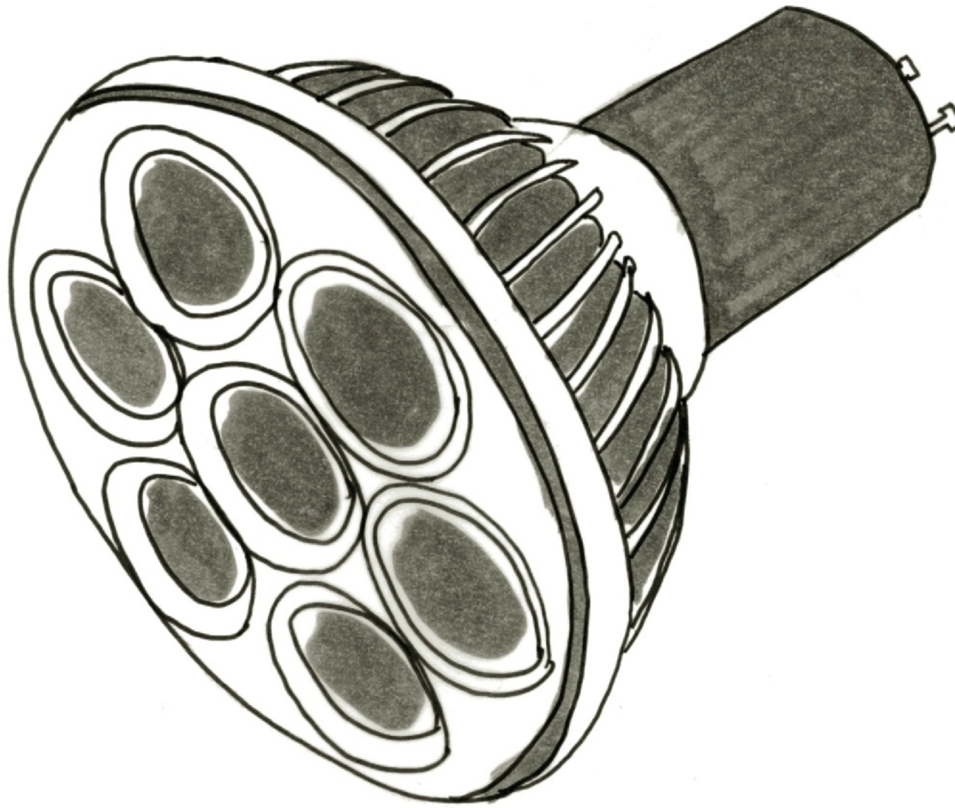


Figure 14.7a Because each light emitting diode (LED) is small and because the emitted light is directional, LED lamps use a cluster of diodes to generate the desired light level and beam width.

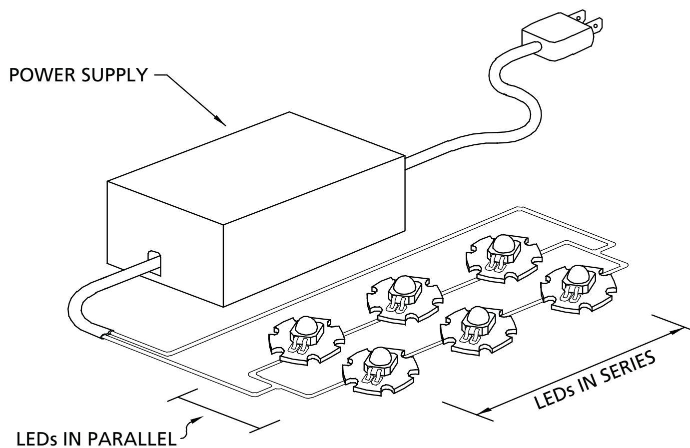


Figure 14.7b Because LEDs are small, most applications use many of them in one lamp/fixture. They are connected to a power supply either in series or parallel. Because the light is produced by many small units, LEDs are ideal for creative, decorative, and task lighting. As their efficacy increases, they are also being used for general area lighting.

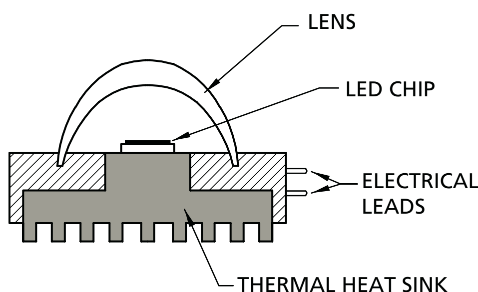


Figure 14.7c An LED used for lighting is the size of a large coin, while the actual light emitting diode (chip) is the size of a tiny coin. The lens directs the light, and the heat sink is necessary to prevent the chip from overheating. Although their efficacy is high, most of the electricity is still converted to heat.

commercially available. At present, they have good efficacy (30–60 lpw), good color rendition (82 CRI), and a good life (about 15,000 hours). In the future it is hoped that they might cover the whole ceiling for creating very diffused even lighting. Thus, in the future OLEDs may be the area sources and LEDs the task lighting sources.

14.8 COMPARISON OF THE MAJOR LIGHTING SOURCES

To help designers choose the best light source for their needs, Table 14.8 compares the major lamp groups by providing the advantages, disadvantages, and major applications for each group.

Some of the most important considerations in choosing a lighting system are the lighting effect desired, color rendition, energy consumption, illumination level, maintenance costs, and initial costs. When we consider energy consumption and illumination level, lamp efficacy (lumens/watt) is the prime factor. Typical ranges of efficacy, as well as lamp life, are found in Table 14.8 as well as in Figure 14.2b.

Table 14.8 Comparison of the Major Lamp Groups

Lamp Group	*Advantages*	*Disadvantages*	*Applications*	*Efficacy (Lumens/Watt)*	*Life (Hours)*
Incandescent	Obsolete except for a few specialty applications such as sparkle in decorative fixtures	Extremely low efficacy (a major burden on the environment); very short lamp life	As decorative light sources in chandeliers and similar fixtures	8–16	800–3000
Halogen	Excellent optical control (e.g., very narrow beams of light are possible) Excellent color rendition (especially warm colors and skin tones) Very low initial cost (especially useful when many low-wattage lamps are used) Flexible (easily dimmed or replaced with another lamp of a different wattage) Very small fixtures are possible No mercury	Very low lamp life (high maintenance costs) Adds high heat load to buildings, thereby increasing cooling load Not good for the environment	For spotlighting, accent, highlighting, and sparkle (residential, restaurants, lounges, museums)	16–30	2000–5000
Fluorescent	Very good for diffused, wide-area, low-brightness lighting Very good to excellent color rendition Very good efficacy Long lamp life	Limited optical control (no narrow beams possible) Sensitive to temperature and, therefore, not used outdoors in cold climates Contains mercury	For diffused even lighting of a large area (offices, schools, residential, industrial)	65–100	20,000–45,000
Compact fluorescent	Relatively small size that allows for small fixtures Can directly replace incandescent lamps in most existing fixtures Good optical control allows some beam control High efficacy Long life Low cost Good to very good color rendition	Color rendition not as good as that of incandescent or halogen lamps that it replaces Beam control limited Contains mercury	Replaces most incandescent and many halogen lamps Good for small fixtures such as table lamps and wall sconces	20–80	8000–15,000
Metal Halide	Good to very good optical control Very good color rendition High efficacy Long lamp life Small fixtures possible	5 to 10 minute delay in start or restart Contains mercury	For diffused lighting or wide beams (offices, stores, schools, industrial, outdoor) Good for high-bay spaces	45–110	10,000–20,000

Lamp Group	*Advantages*	*Disadvantages*	*Applications*	*Efficacy (Lumens/Watt)*	*Life (Hours)*
Ceramic metal halide	Small size allows for small fixtures Very good beam control Very good color rendition Very good replacement for halogen lighting, with four times its life and efficacy	Color rendition is not quite as good as that of the halogen lamps it replaces Contains mercury	Very good replacement for halogen lamps Spot and highlighting	40–80	10,000–15,000
High Pressure Sodium	Good optical control Very high efficacy Very long lamp life	Color rendition is poor (mostly orange and yellow) About 5-minute delay in start or restart Contains mercury	For diffused lighting or wide beams where color is not important (outdoor, industrial, warehouses, interior and exterior floodlighting)	45–140	24,000–35,000
LED (light-emitting diode)	Very small source Very durable Long to extremely long life Excellent source of pure colors such as red, green, blue, etc. No mercury Potential to become a major light source Good source for small amount of white light, as in task lights	Still expensive Not good for diffused large-area lighting	Decorative lighting, especially in pure colors Accent lighting Task lighting Exit and emergency directional lighting Wayfinding Canned downlights Replacement for reflector lamps	30–110	30,000–90,000

14.9 LUMINAIRES

Lighting fixtures, also called luminaires, should not be confused with luminaries, which refer either to Mexican Christmas lanterns or to persons of brilliant achievement who have shed light on the unknown. Luminaires have three major functions: supporting the lamp with some kind of socket, supplying power to the lamp, and modifying the light from the lamp to achieve a desired light pattern and to reduce glare. Typical luminaires are divided into six generic categories by the way they distribute light up or down (Table 14.9).

Table 14.9 Lighting Fixtures (Luminaires)

Illustration	Distribution of Light (% directed up/ % directed down)	Type
	0–10 90–100	*Direct:* Direct lighting fixtures send most of the light down to the workplane. Since little light is absorbed by the ceiling or walls, this is an efficient way to achieve high illumination on the workplane. Direct glare and veiling reflections are often a problem, however. Also, shadows on the task are a problem when the fixture-to-fixture spacing is too large.
	10–40 60–90	*Semidirect:* Semidirect fixtures are very similar to direct luminaires except that a small amount of light is sent up to reflect off the ceiling. Since this creates some diffused light as well as a brighter ceiling, both shadows and the apparent brightness of the fixtures are reduced. Veiling reflections can still be a problem, however.
	40–60 40–60	*General diffuse:* This type of fixture distributes the light more or less equally in all directions. The horizontal component can cause severe direct glare unless the diffusing element is large and a low-wattage lamp is used.
	40–60 40–60	*Direct–indirect:* This luminaire distributes the light about equally up and down. Since there is little light in the horizontal direction, direct glare is not a severe problem. The large indirect component also minimizes shadows and veiling reflections.
	60–90 10–40	*Semi-indirect:* This fixture type reflects much of the light off the ceiling and, thus, yields high-quality lighting. The efficiency is reduced, however, especially when the ceiling and walls are not of a high-reflectance white.
	90–100 0–10	*Indirect:* Almost all of the light is directed up to the ceiling in this fixture type. Therefore, ceiling and wall reflectance factors must be as high as possible. The very diffused lighting eliminates almost all direct glare, veiling reflections, and shadows. The resultant condition is often used for ambient lighting.

Luminaires with a sizable direct component are most appropriate when high illumination levels are required over a large area or when the ceiling and walls have a low reflectance factor. Although their energy efficiency is high, the quality of light is usually not. Direct glare, veiling reflections, and unwanted shadows are all reduced or eliminated by the fixtures with a large indirect component. Task/ambient lighting provides the best of both approaches and is discussed further below.

The quality of the lighting from direct fixtures can be significantly improved by the design of the fixtures. The following section describes the various techniques used to improve these types of luminaires.

Use not only high-efficacy lamps but also high-efficiency luminaires!

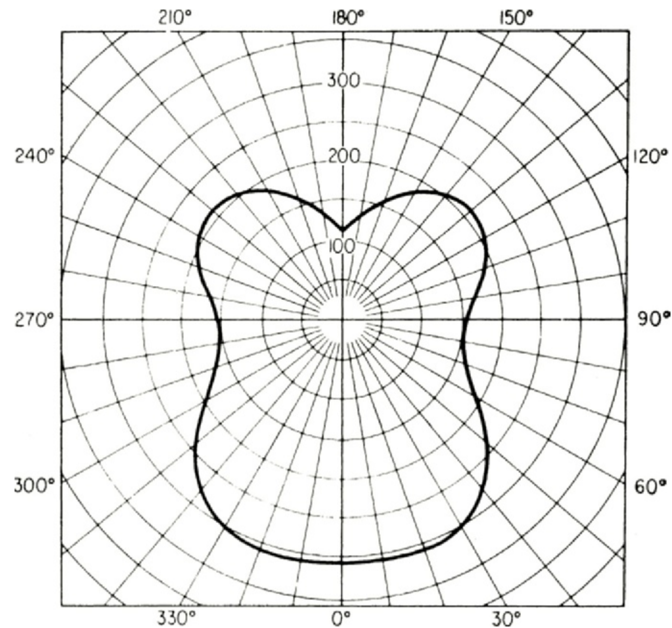


Figure 14.10a Manufacturers generally supply candlepower (candela) distribution curves for their lighting fixtures. In this vertical section, the distance from the center determines the intensity of the light in that direction. This curve is for a semidirect lighting fixture. (Courtesy of Osram Sylvania.)

14.10 LENSES, DIFFUSERS, AND BAFFLES

The distribution of light from a luminaire (in a vertical plane) is often defined by a curve on a polar-coordinate graph, where the distance from the center represents the candlepower (candelas) in that direction. The candlepower distribution curve of a semidirect lighting fixture is shown in Figure 14.10a. The up-directed light will reflect off the ceiling to reduce both direct glare and veiling reflections. For the same goal, some direct-lighting fixtures are designed to distribute light in a batwing light pattern (Fig. 14.10b). The high-angle light that causes the direct glare and the low-angle light that causes the veiling reflections are thereby avoided as much as possible.

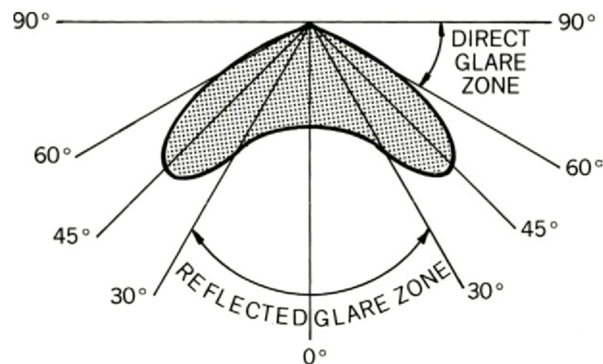


Figure 14.10b For luminaires that have no uplight, only the bottom half of the polar coordinate graph is shown. Light that leaves the luminaire from the 0 to 30° zone tends to cause veiling reflections and reflected glare, while light in the 60 to 90° zone tends to cause direct glare. Fixtures with batwing light-distribution patterns yield a better-quality light because they minimize the light output in these problematic zones. However, they are not ideal when computers are used.

Because the brightness of a room is judged largely by the brightness of the walls, wallwasher luminaires are sometimes used. Often asymmetric luminaires are used to illuminate the wall evenly (Fig. 14.10c).

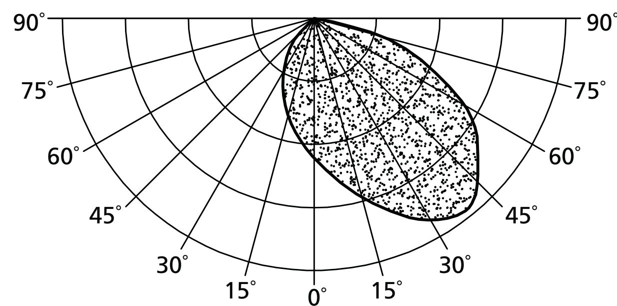


Figure 14.10c Wallwashers are used to make rooms look brighter and larger.

Lenses, prisms, diffusers, baffles, and reflectors are all used in fixtures

to control the manner in which light is distributed from the lamps.

Baffles, Louvers, and Eggcrate Devices

These devices limit direct glare by restricting the angle at which light leaves the fixture (Fig. 14.10d). If these devices are painted white, they, in turn, could become a source of glare. If, on the other hand, they are painted black, much of the light is absorbed and the efficiency of the fixture is very low. These devices can be small and part of the luminaire, or they can be large and part of the architecture (e.g., waffle slab or joists). One-way baffles, such as louvers, joists, and beams, are useful only if viewed perpendicular to their direction (Fig. 14.10e).

Parabolic Louvers

This type of louver is made of parabolic wedges with a specular finish (Fig. 14.10f). These devices are extremely effective in preventing direct glare because the light distribution is almost straight down. Thus, these fixtures have a high visual comfort probability (VCP). They are also very good in preventing veiling reflections in computer monitors (Fig. 14.10g). The penalty for having mostly vertical light is that vertical surfaces such as walls are not well illuminated. This type of louver also does not solve the problem of veiling reflections on horizontal surfaces.

Diffusing Glass or Plastic

Translucent or surface-frosted sheets diffuse the emitted light more or less equally in all directions. The horizontal component of this distributed light is a cause of significant direct glare. Consequently, these devices have limited usefulness.

Lenses and Prisms on Clear Sheets

When the surface of clear sheets of glass or plastic is formed into small lenses or prisms, good optical control is possible. The light is refracted so that more of the distribution is down and direct glare is reduced. Round fixtures can use Fresnel lenses that can either concentrate the light like a convex lens or disperse the light like a concave lens. Fresnel lenses are much less expensive than regular lenses because they consist of flat sheets with beveled grooves (Fig. 14.10h).

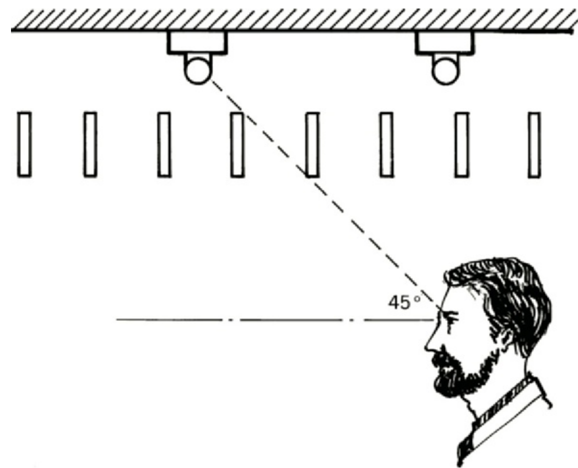


Figure 14.10d Baffles, louvers, and eggcrates are used to shield against direct glare. The direct view of the light sources should be shielded up to at least 45°.



Figure 14.10e One-way baffles are effective only when people are limited to viewing the ceiling from one direction. For example, in a corridor, the baffles should be oriented perpendicular to the length of the corridor. Use eggcrates when shielding is required in two directions.

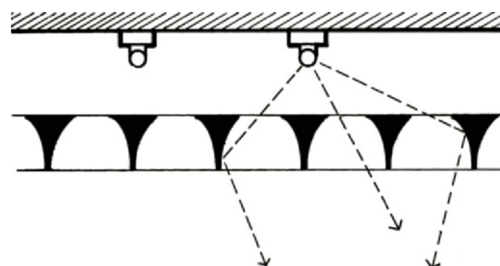


Figure 14.10f Parabolic louvers are very effective in reducing direct glare.





Figure 14.10g The left photo shows the room after the luminaire lenses were replaced with parabolic louvers. The reduction in direct glare and veiling reflections in the computer monitor at the left and center is very significant. However, notice that while horizontal surfaces are brighter, vertical surfaces are darker. (Note the brightness of the stack of books on the left side of each photo). To counter the negative effect of dark walls that results from parabolic louvers, a wallwasher was added (compare the right rear walls). (Courtesy of American Louver Company.)

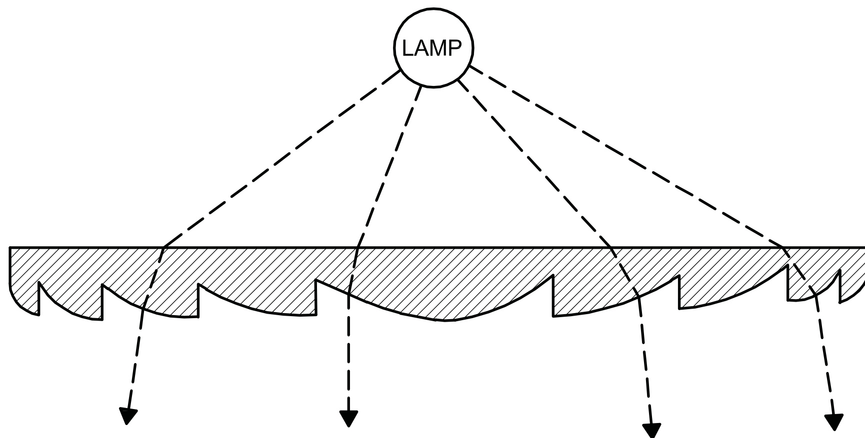


Figure 14.10h Lenses and prisms refract the light down to reduce direct glare. Fresnel lenses are made of thin plates but act as if they were thick convex or concave lenses. The light bends twice: on entering glass and on leaving glass.

14.11 LIGHTING SYSTEMS

Lighting systems can be divided into six generic types. In many applications, a combination of these basic systems is used.

General Lighting

General lighting usually consists of more or less uniformly spaced, ceiling-mounted direct lighting fixtures (Fig. 14.11a). It is a very popular system because of the flexibility in arranging and rearranging work areas. Since the illumination is roughly equal everywhere, furniture placement is relatively easy. The energy efficiency is usually low because noncritical work areas receive as much light as task areas. Light quality, especially veiling reflections, is also a problem, since it is hard to find a work area that does not have a lighting fixture in the offending zone (see Fig. 12.11k).

Localized Lighting

Localized lighting is a nonuniform arrangement in which the lighting fixtures are concentrated over the work areas (Fig. 14.11b). Fairly high efficiency is possible since nonwork areas are not illuminated to the same degree as work areas. Veiling reflections and direct glare can be reduced because this system affords some freedom in fixture placement. Flexibility in rearranging the furniture, however, is reduced.

Ambient Lighting

Ambient lighting is indirect lighting reflected off the ceiling and walls. It is a diffused, low-illumination, level lighting that is sufficient for easy visual tasks and circulation. It is usually used in conjunction with task lighting and is then known as task/ambient lighting. Direct glare and veiling reflections can be almost completely avoided with this approach. The luminaires creating the ambient lighting can be suspended from the ceiling, mounted on walls, supported by pedestals, or integrated into the furniture (Figs. 14.11c–14.11f). To prevent hot spots, the indirect fixtures should be at least 12 in. (30 cm) below the ceiling, and to prevent direct glare, they should be above eye level (Fig. 14.11d). The ambient illumination level should be about one-third of the task light level.

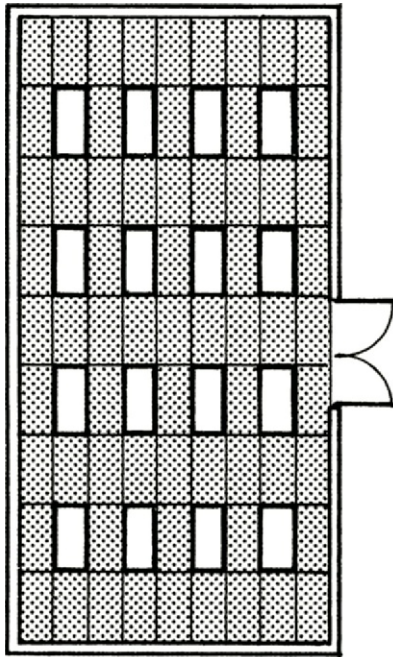


Figure 14.11a This reflected-ceiling plan shows the regular layout of direct luminaires, which is typical of general lighting systems. This approach is very flexible but not very energy efficient or interesting.

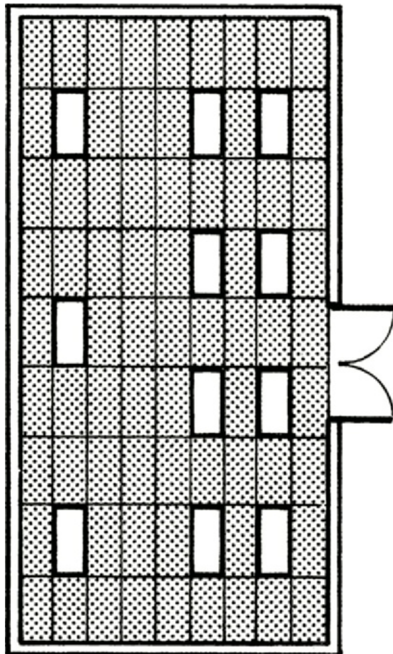


Figure 14.11b This reflected-ceiling plan illustrates localized lighting. In this system, direct fixtures are placed only where they are needed. Veiling reflections and direct glare are reduced. It is also efficient but is not very flexible.

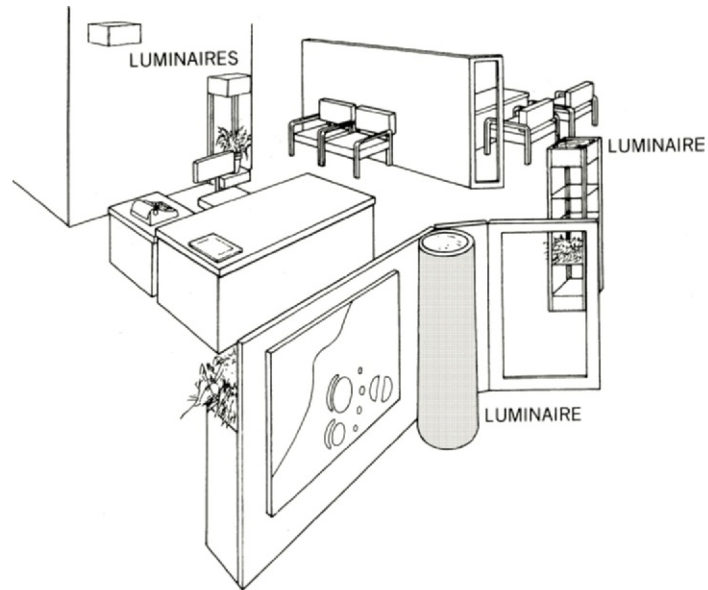


Figure 14.11c Ambient lighting provides a soft, diffused light from indirect fixtures. This diagram shows the luminaires mounted either on pedestals (torchieres) or on the wall (sconces). (Courtesy of Cooper Lighting.)

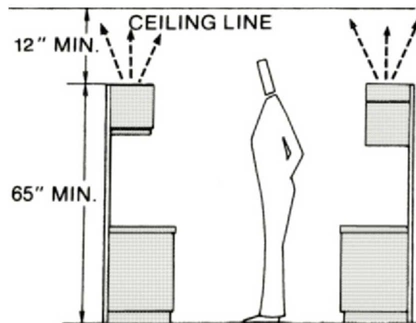


Figure 14.11d Ambient lighting from furniture-integrated lighting fixtures is shown. (Courtesy of Cooper Lighting.)



Figure 14.11e Ambient lighting from pendent indirect luminaires, together with task lighting on desks, creates high-quality task/ambient lighting. (Courtesy of Peerless Lighting Corporation.)

Task Lighting

The greatest flexibility, quality, and energy efficiency are possible with task lighting usually attached to or resting on the furniture (Figs. 14.11e and 14.11f). Direct glare and veiling reflections can be completely prevented when the fixtures are placed properly (see Fig. 12.13a). Since only the task and its immediate area are illuminated, the energy efficiency is also very high. The individual control possible with this personal lighting system can have significant psychological benefits for workers, who traditionally have little influence over their environment. To avoid dark surrounding areas and excessive brightness ratios, some background illumination is required. Since indirect luminaires are often used to complement the task lighting, this combination is known as **task/ambient lighting**. Not only is task/ambient lighting the most sustainable by using less energy than standard lighting, it is also the highest-quality lighting.

Use task/ambient lighting whenever possible!

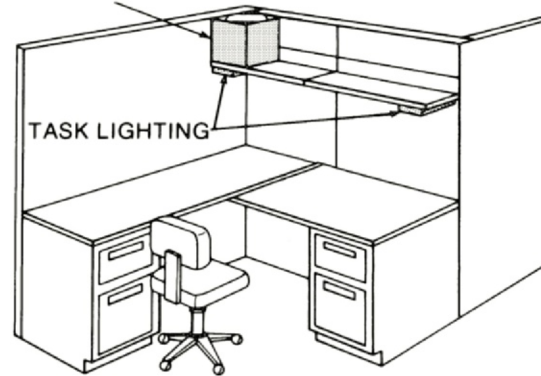


Figure 14.11f Note how the task lights are mounted on each side and not in front of the work area because of the problem of veiling reflections. Since an indirect luminaire is included in the office furniture, this system is known as task/ambient lighting. (Courtesy of Cooper Lighting.)

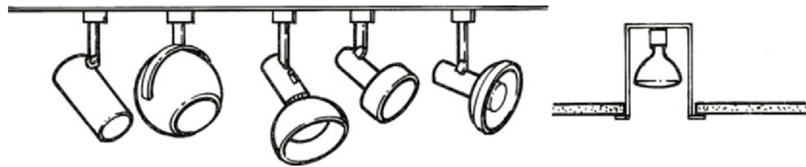


Figure 14.11g Accent lighting is usually achieved with track lighting or canned downlights. To highlight only small areas or objects, LED or low-voltage fixtures with narrow beams of light are especially appropriate. Instead of a centrally located step-down transformer, each luminaire can have its own small transformer.

Accent Lighting

Accent lighting is used whenever an object or a part of the building is to be highlighted (Fig. 14.11g). Accent illumination should be about ten times higher than the surrounding light level. Since this type of lighting is very variable and is a very powerful generator of the visual experience, designers should give it careful attention.

Decorative Lighting

With a decorative-lighting system, unlike all of the others, the lamps and fixtures themselves are the object to be viewed (e.g., chandeliers). Although glare is in this case called "sparkle," it can still be annoying if it is too bright or if a difficult visual task has to be performed. In most cases, the decorative lighting also supplies some of the functional lighting.

White or very light-colored walls, ceilings, and furniture are an important component of sustainable lighting!

14.12 REMOTE-SOURCE LIGHTING SYSTEMS

In remote-source lighting systems, light is efficiently transmitted inside a light guide by the phenomenon of total internal reflection. When the light enters the light guide as a sufficiently narrow beam, the walls of the light guide behave like perfect mirrors. Light guides can be made of hollow plastic pipes, solid plastic rods, or fibers of glass or plastic. Because of the need for narrow beams to enter the light guides, direct sunlight and small, compact light sources are best. The light guides can be designed to be end-emitting or side-emitting to form a linear light source. Remote-source lighting has many benefits: filtering out ultraviolet and infrared energy, separating the light from almost all of the heat generated by the lamp, removing the light source from a hazardous area, simplifying maintenance, and reducing energy consumption.

Light pipes are made of a prismatic, plastic film with a narrow-beam light source at one end (Fig 14.12a). For use as a linear diffuser, a mirror is placed at the opposite end, and a special diffusing film is placed where the light is to be extracted. Mirrors are also used to make turns in the otherwise straight pipes. Light pipes can deliver large amounts of light to areas difficult or dangerous to reach for relamping. Applications include outlining the tops of skyscrapers and illuminating large and high spaces, such as airplane hangars.

Fiber-optic lighting uses special flexible plastic rods or fibers of plastic or glass to guide the light. A very narrow-beam light source is needed,

because the light must enter the fibers almost parallel to their length in order for total internal reflections to occur (Fig. 14.12b). The main applications are for the display of ultraviolet sensitive objects (museums), small objects (crystal and jewelry), and objects that need to remain cool (chocolate).

Fiber-optic lighting is also appropriate for decorative or functional lighting where numerous small-light sources and the convenience of one centralized lamp are desired. Troublesome electric wires connected to lamps can be replaced by water-resistant, safe optical fibers. Flexible plastic rods that look a little like neon lighting are used to show direction, create patterns and signs, and safely illuminate pools.

Light can also be transmitted by the use of mirrors and lenses. This kind of beamed lighting was described in Section 13.16.

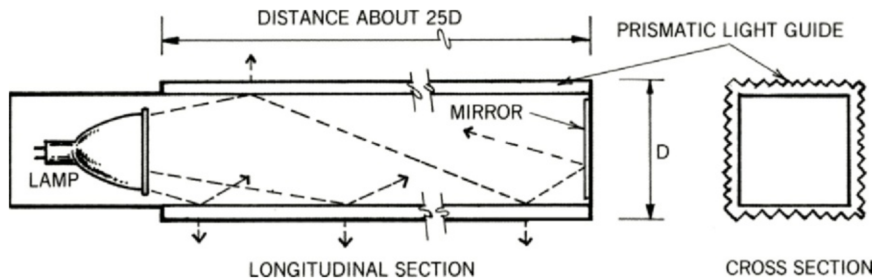


Figure 14.12a Light guides, or light pipes, convey light a distance of about 25 diameters. The light can be conveyed to the end with small losses, or a linear light source can be created by modifying the light guide to increase the losses along its length.

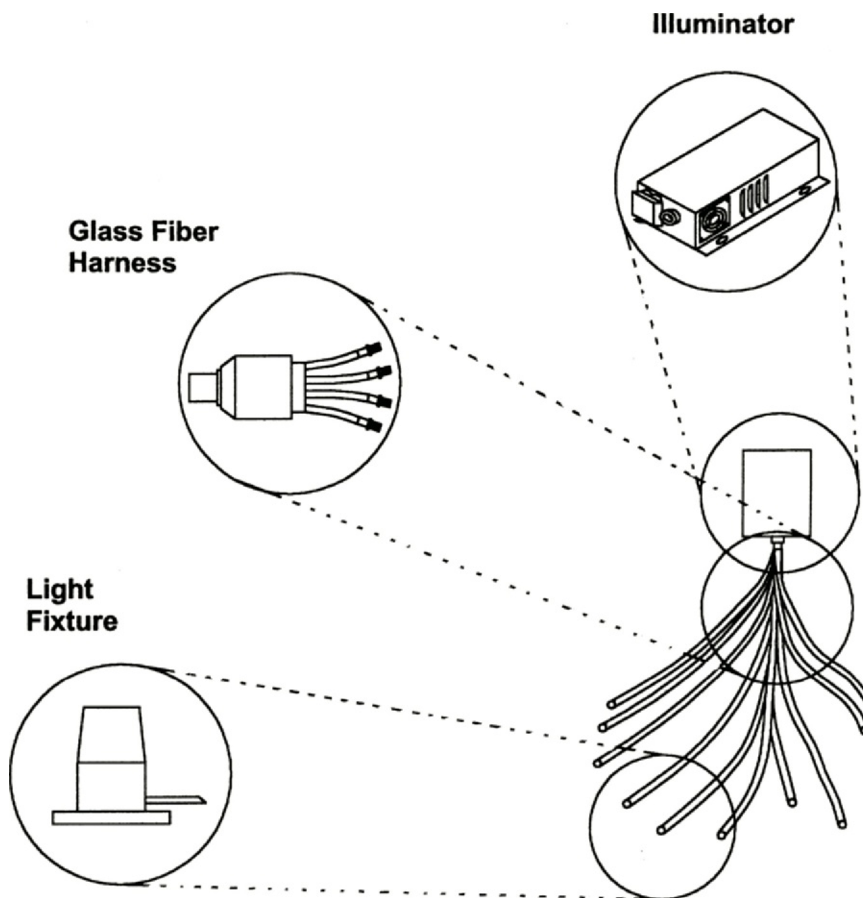


Figure 14.12b A fiber-optic lighting system consists of a light source (can contain a rotating color wheel), a fiber harness, and lighting fixtures that can deliver the light in any pattern desired from beam to diffused source. (Courtesy of Lucifer Lighting Co.)

14.13 VISUALIZING LIGHT DISTRIBUTION

For both electric lighting and daylighting, it is very valuable to develop an intuitive understanding of the light distribution from various sources. To calculate the illumination from a point light source, see Sidebox 14.13.

Let us first consider how illumination changes with distance from various light sources. For a point light source, the illumination (footcandles [lux]) is inversely proportional to the square of the distance. Notice that in Figure 14.13a when the distance doubles (1 to 2), the illumination is reduced to one-fourth (100 to 25). In most applications, incandescent and high intensity discharge lamps can be treated as point sources. The main implication of this principle is that point sources should usually be as close as possible to the visual task.

A line source of infinite length is shown in Figure 14.13b. In this case, the illumination is inversely proportional to the distance. When the distance is doubled (1 to 2), the illumination is halved (100 to 50). A long string of fluorescent lamps would create such a situation.

A surface source of infinite area is shown in Figure 14.13c. In this case, the illumination does not vary with distance. A typical example of this kind of light source would be well-distributed indirect lighting in a large room. See Section 13.4 for visualizing the illumination from a finite area source.

The illumination also does not change with distance in a parallel beam of light. It is extremely difficult, however, to create a parallel beam, as was explained in Figure 14.3c.

SIDEBOX 14.13

Illumination from a point light source is proportional to the candlepower and inversely proportional to the square of the distance.

$$\text{Footcandles} = \frac{\text{candlepower}}{(\text{feet})^2}$$

$$\text{fc} = \frac{\text{cd}}{(\text{ft})^2}$$

Example: What is the illumination on the ground directly under a streetlight that is 20 ft high and has a light intensity of 10,000 cp straight down?

$$\text{fc} = \frac{\text{cd}}{(\text{ft})^2} = \frac{10{,}000}{20^2} = 25\,\text{fc}$$

or in SI

$$\text{Lux} = \frac{\text{candela}}{(\text{meter})^2} = \frac{\text{cd}}{\text{m}^2}$$

Example: What is the illumination on the ground directly under a streetlight that is 7 m high and has a light intensity of 15,000 cd straight down?

$$\text{Lux} = \frac{\text{cd}}{\text{m}^2} = \frac{15{,}000}{(7)^2} = 306\ \text{lux}$$

Of the common light sources used in buildings, only direct sunlight acts as a beam of parallel light. However, luminaires with optics can come close.

The above discussion demonstrated how illumination varies with distance from the source. The following discussion will describe how the light from a fixed source is distributed over the workplane. Two major ways exist to graphically display the illumination at the workplane. The first uses points of equal illumination to plot the contour lines of the light pattern in plan. Figure 14.13d illustrates

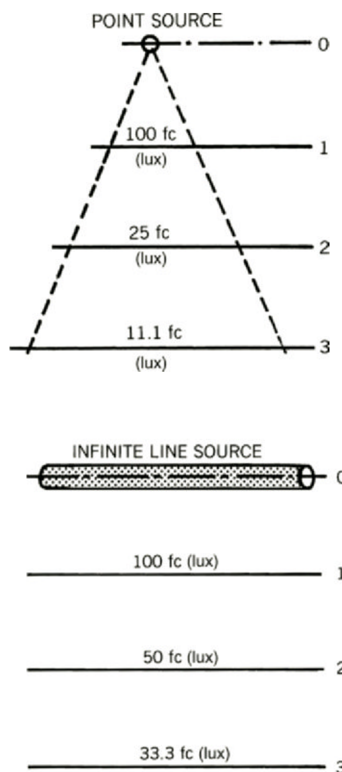


Figure 14.13a The illumination from a point source is inversely proportional to the square of the distance (feet, meters, or any other unit).

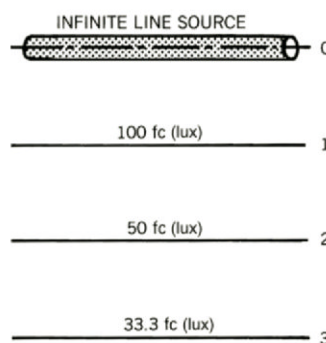


Figure 14.13b The illumination from a line source of infinite length is inversely proportional to the distance.

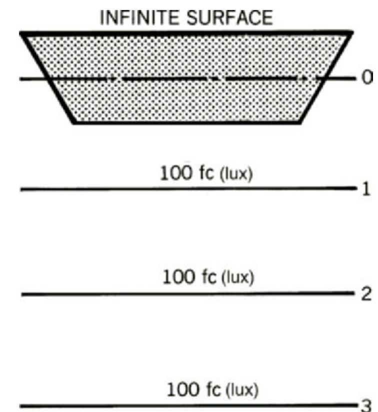


Figure 14.13c The illumination from a surface of infinite area is constant with distance.

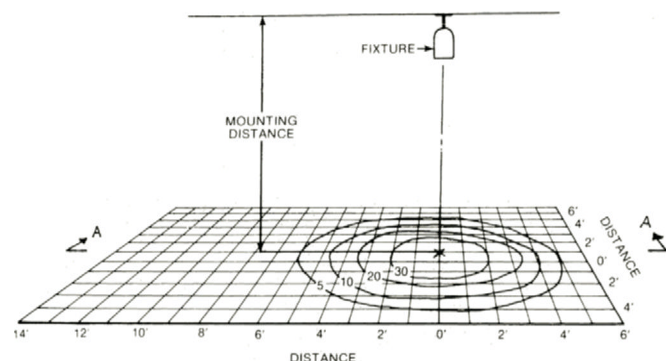


Figure 14.13d This graphic presentation of the illumination pattern is generated from isofootcandle (isolux) lines connecting points of equal illumination. (Courtesy of Cooper Lighting.)

this method for a common light source aimed straight down. Note the concentric pattern of isofootcandle (isolux) rings. In Figure 14.13e, we see the pattern created when the same source is not aimed straight down. Note that the intensities are less, but the area of illumination is greater. This is another example of the consequence of the cosine law, which was explained in Figure 6.5c. Figure 14.13f illustrates this method as applied to outdoor lighting.

The second graphic method shows a graph of the light distribution superimposed on a section of the room. Figure 14.13g uses this method to show the same lighting situation shown in Figure 14.13d, but only at section A–A. Similarly, Figure 14.13h shows section B–B of the pattern shown in Figure 14.13e. When more than one fixture is used, the effect of each is combined for the total because illumination is additive (Fig. 14.13i).

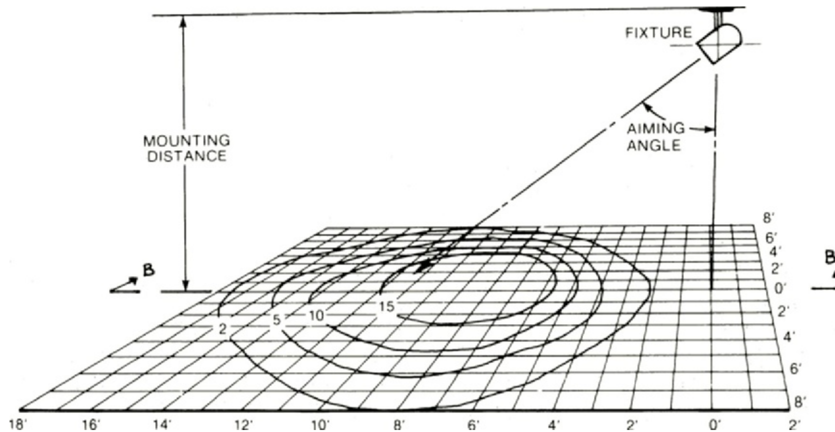


Figure 14.13e When light is not aimed straight at a surface, the isofootcandle (isolux) lines are elongated. The lines are now of reduced intensity and cover a larger area. (Courtesy of Cooper Lighting.)

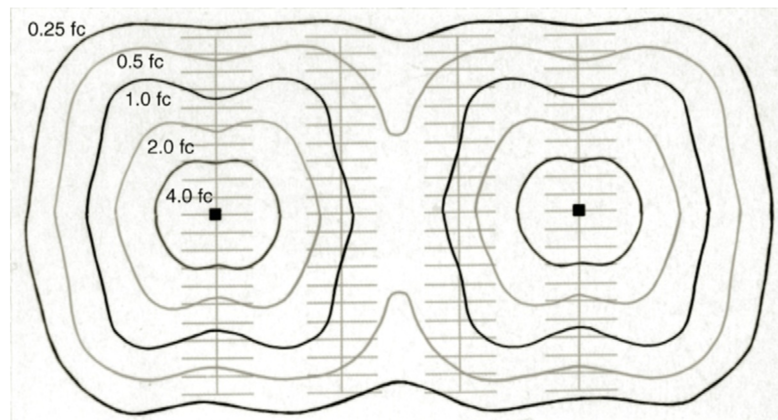


Figure 14.13f Isofootcandle (isolux) lines used to define the lighting pattern from parking-lot lighting. (Courtesy of Spaulding Lighting, Inc.)

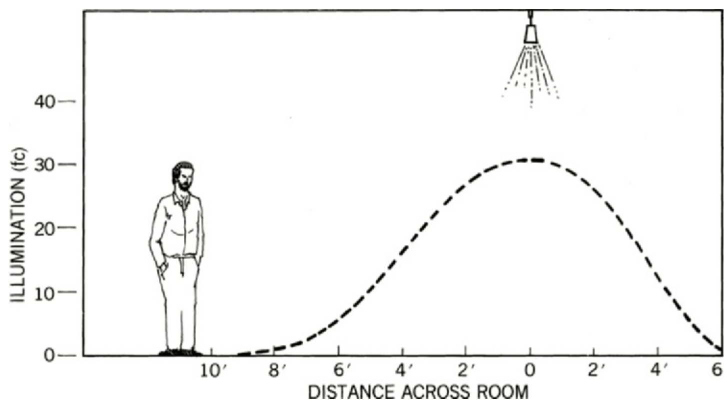


Figure 14.13g In this alternate graphic method of defining the lighting pattern, a curve of the illumination across a room is plotted on top of a section of the space. This diagram, in fact, is section A–A of the room in Figure 14.13d.

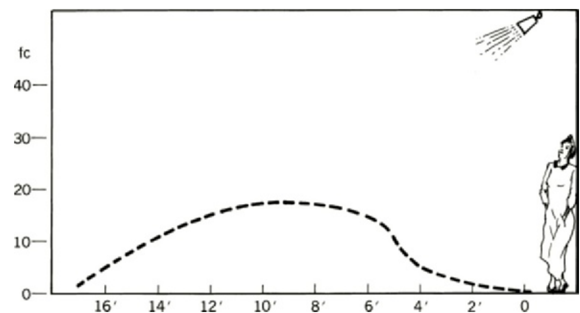


Figure 14.13h This diagram plots the illumination across the room at section B–B of Figure 14.13e. Again, we can see that when the light source is not aimed normal (perpendicular) to the workplane, the maximum illumination is reduced and the light is spread over a larger area.

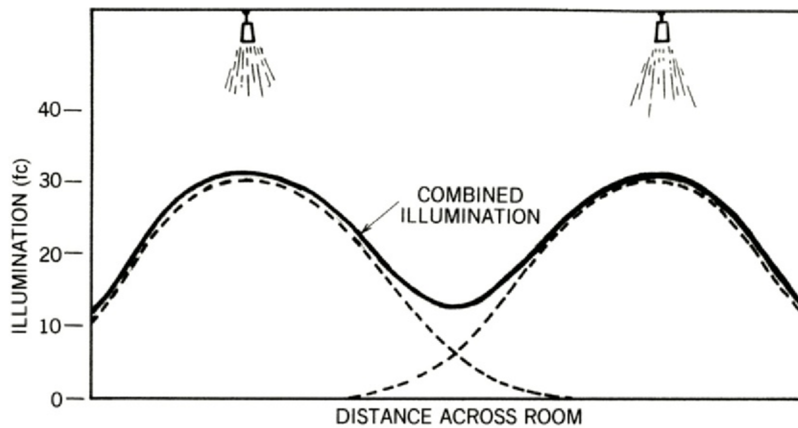


Figure 14.13i When more than one light source is present, the curve defining the combined effect is the sum of the individual curves.

14.14 ARCHITECTURAL LIGHTING

The lighting system can either consist of prefabricated luminaires or be an integral part of the building fabric. In the latter case, it is often known as architectural lighting. Ceiling-based systems will be discussed first.

Cove Lighting

Indirect lighting of the ceiling from continuous wall-mounted fixtures is called cove lighting (Fig. 14.14a). Besides creating a soft, diffused ambient light, coves create a feeling of spaciousness because bright surfaces (in this case the ceiling) seem to recede. The cove must be placed high enough so that a direct view of the light source is not possible, and at the same time it must be far enough from the ceiling to prevent excessive brightness (hot spots) right above the lamps. The inside of the cove, the upper walls, and the ceiling must all be covered with a high-reflectance white paint. Larger rooms require cove lighting on two, three, or four sides.

Coffer Lighting

Coffers (pockets) in the ceiling can be illuminated in a variety of ways. Large coffers can have cove lighting around their bottom edges (Fig. 14.14b), which makes them appear similar to skylights. This technique is sometimes used inappropriately on real skylights as nighttime illumination. In such a design, most of the light is lost through the skylight. Furthermore, simulating daylight at night is not only aesthetically inappropriate but also confusing to our circadian rhythms. Small coffers can be illuminated by recessed luminaires (Fig. 14.14c).

Luminous-Ceiling Lighting

The luminous ceiling provides a large area source of uniform illumination by means of continuous

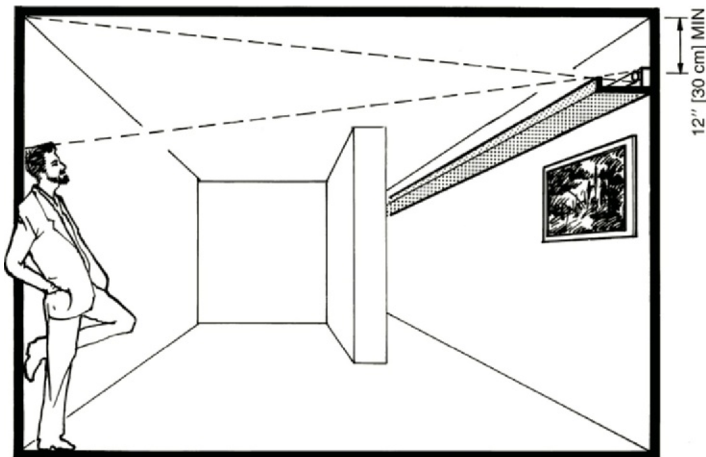


Figure 14.14a Ceilings appear to recede with cove lighting. Lamps must be shielded from view.

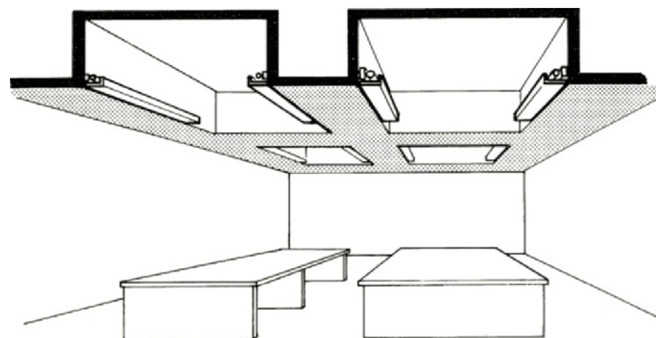


Figure 14.14b Large coffers can be illuminated with cove lighting.

diffuser elements suspended below uniformly spaced fluorescent lamps (Fig. 14.14d). The mind often associates this uniform high-brightness ceiling with a gloomy overcast sky. In the worst case, it is similar to being in a fog, where the lighting is so diffused that the three-dimensional world appears rather flat. Another problem is that if a lamp burns out, a disturbing dark spot appears. For these and several other practical reasons, luminous ceilings are not used much anymore.

Wall Illumination

Although most visual tasks take place on the horizontal plane, the vertical surfaces have the greatest visual impact (see Figs. 12.10c and 12.10d). When we experience architecture, we are usually viewing vertical surfaces. Functional lighting systems for horizontal workplanes sometimes do not sufficiently illuminate the walls. Supplementary lighting fixtures mounted on the ceiling or walls can increase the brightness of the walls, emphasize texture, or accent certain features on the walls. Architectural lighting in the form of valances, cornices, and luminous panels is often used to illuminate the walls.

Valance (Bracket) Lighting

Valance (bracket) lighting illuminates the wall both above and below the shielding board (Fig. 14.14e). The placement and proportion of valance boards must result in complete shielding of the light sources as seen from common viewing angles. Valances should be placed at least 12 in. (30 cm) below the ceiling to prevent excessive ceiling brightness (hot spots). If the valance must be close to the ceiling, a cornice, as described below, might be more appropriate.

Cornice (Soffit) Lighting

When a valance board is moved up to the ceiling, it is called a cornice (Fig. 14.14f). The wall is then illuminated only from above, and the ceiling, which receives no light from the cornice, might appear quite dark.

This is called **cornice lighting** or **soffit lighting**. If people are permitted to approach the wall, the light source will be visible unless additional shielding is provided. Cross louvers are quite effective in preventing this direct glare situation (Fig. 14.14g).

Luminous Wall Panels

Luminous wall panels must have very low surface brightness to prevent direct glare or excessive brightness ratios. Nevertheless, the viewer might feel frustrated because the luminous panel implies a window where the view to the outside is denied. The same sense of frustration often exists with the use of translucent glazing in real windows.

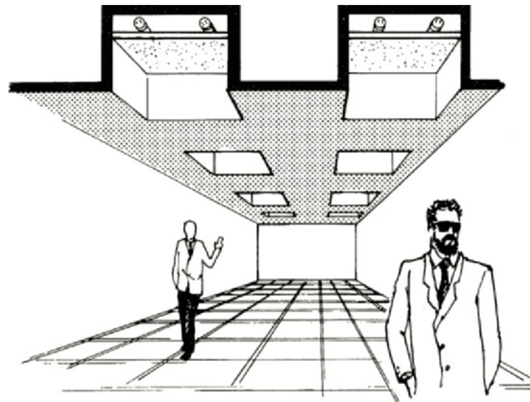


Figure 14.14c Small coffers can be illuminated by direct luminaires in each coffer.

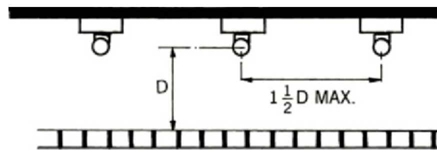


Figure 14.14d The very even brightness of luminous ceilings can create difficulties. Not only is it technically difficult to achieve and maintain, but it also tends to simulate a gloomy overcast sky.

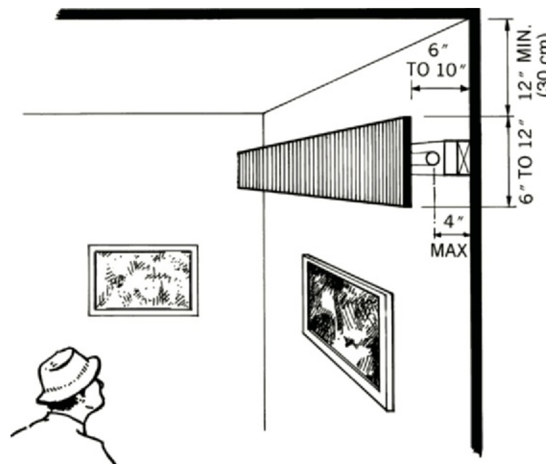


Figure 14.14e Valance lighting can increase the wall brightness, which is very important in the overall visual appearance of a space. The specific design of a valance depends greatly on the expected viewing angles in a particular room.

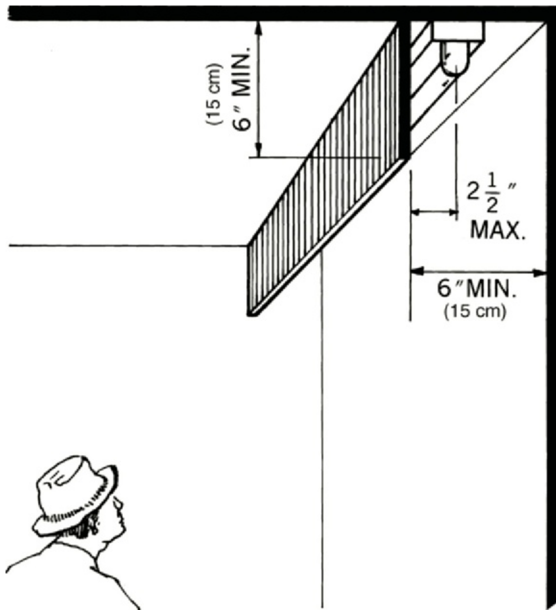


Figure 14.14f Because cornice lighting illuminates only the walls and not the ceiling, excessive brightness ratios can occur.

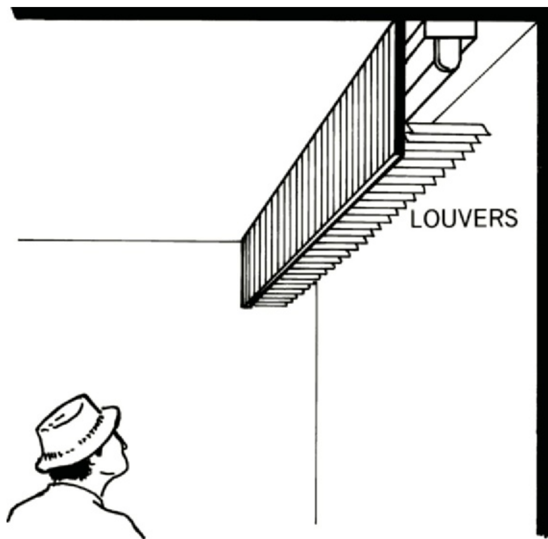


Figure 14.14g In many cases, the viewing angles are such that direct glare will result unless louvers or some other shielding devices are used in the cornice.

14.15 OUTDOOR LIGHTING

Like indoor lighting, outdoor lighting has both functional and aesthetic consideration, and as with indoor lighting, energy conservation is now a major consideration. In addition, it has become apparent that there are such things as light pollution and light trespass.

All animals, including humans, need darkness. Out circadian rhythms are interrupted when we are not exposed to enough darkness. Light trespass from our neighbors' lights can interfere with our production of melatonin, which in turn has an adverse effect on our health. There is also much scientific evidence that other animals are also greatly affected by light pollution. For example, sea turtles can't reproduce, birds fly into buildings, and trees grow and lose their leaves at the wrong time of year.

Because much of humanity cannot see the Milky Way anymore and because astronomers are inhibited in their work by light pollution, the International Dark Sky Association (www.darksky.org) was formed. This organization has increased awareness of light pollution and light trespass. As a consequence, many communities are passing ordinances to control both of these problems.

Light pollution is wasted light!

Outdoor Area Lighting

The major steps in reducing light pollution are to reduce the illumination level used outdoors, to not use luminaires that allow light to go up into the sky and onto a neighbor's property, and to turn lights off when not needed (e.g., do not illuminate a parking lot when it is not used). Outdoor lighting should be controlled not only by a photocell switch to prevent lights from being on during daylight hours, but also by a timer so that lights go off when they are no longer needed. Also, **full cutoff** luminaries should be used to minimize the light going up into the sky.

Light trespass is avoided by the careful location and selection of luminaires. **Photometric** data in the form of candlepower (candela) curves describes the angles at which light is emitted from a fixture. Near property lines, asymmetric luminaires should be used (Fig. 14.10c).

Outdoor Building Illumination

Buildings should be illuminated from the top rather than from below, which is, unfortunately, the common practice (Fig. 14.15). There are many benefits to reversing this situation: With fixtures aimed down, light missing or reflected off the building does not pollute the sky but rather illuminates the ground around the building. Lights facing down also collect less dirt.

Furthermore, fixtures mounted on the ground aiming up at the building often cause serious glare problems (Fig. 14.15). Lighting fixtures

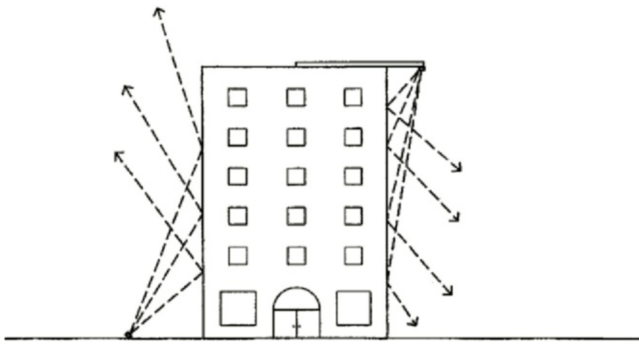


Figure 14.15 When buildings are illuminated from below, which is the common situation, much of the light spills into the night sky (left side of the building). By illuminating buildings from above instead, this spilled light illuminates the landscape around the building (right side of the building).

around the top of the building can be an aesthetic asset rather than a liability. Throughout most of history, buildings ended with a "cap" of some kind, and architects are again seeking to make the tops of their buildings more interesting. A common device is to have a large ring around the top of building to support window-washing equipment. Such a cap could easily support lighting fixtures aimed at the building.

Landscape Lighting

Landscape lighting should not try to simulate daylighting, but rather create a magical world where trees are illuminated from below and seen against a black sky. Special low-voltage (12-volt) fixtures are generally used because of their safety and economy. Because there is no shock hazard with low voltage, the electrical installation becomes simpler and less expensive. However, a step-down transformer is required, and the electrical conductors need to be much larger than those required for line voltage. To prevent light pollution, use uplighting sparingly and make sure it is mostly intercepted by the leaves of the trees.

14.16 EMERGENCY LIGHTING

Emergency lighting is required by code to allow people to safely exit a building. Exits must be clearly marked, and a lighted path must be provided even if there is a power failure of the normal lighting. Special lighting fixtures and exit signs are provided that will receive power from either a battery or an emergency generator when normal power is lost.

Exit signs are an ideal application for LED lamps, since they require a very long-lived, monochromatic, and low-power light source. The typical exit sign in the United States is red, while in most of the world it is green. Another problem with the existing system is that in case of fire, smoke rises and obscures high exit signs. For this reason, airlines have lighted strips on the floor to guide people to the exits. These lighted strips on the floor or on the lower wall need not be electrified, because photoluminescent materials can be used. Such materials absorb light and continue to glow even when no longer illuminated (Fig. 14.16). Although the

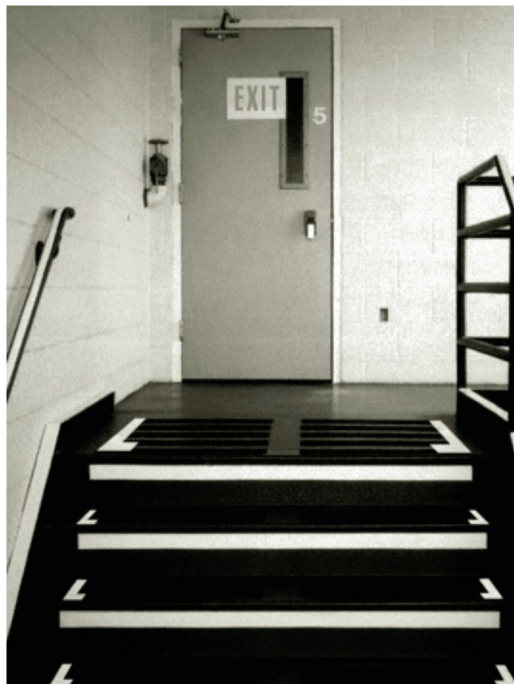




Figure 14.16 Besides illuminated exit signs and directional lighting for emergencies, photoluminescent signs and strips can be used. These phosphorescent materials glow in the dark even with the loss of all electrical power. (Photos courtesy of 3M.)

brightness of the glow decreases with time, they are usually needed soon after the power failure. Consequently, the photoluminescent material can successfully guide people out of buildings in an emergency when the normal lighting is not functioning.

14.17 CONTROLS

Properly designed switching can yield functional, aesthetic, psychological, economic, and environmental benefits. Switching allows for the flexible use of spaces, as well as the creation of interesting and varying lighting environments. As mentioned before, the definition of personal space and the control over one's environment are important psychological needs that are partially satisfied by individual work area switching. Switching is also one of the best ways to conserve large amounts of energy (money and environment) simply by allowing unneeded lights to be turned off.

Automatic lighting controls can reduce lighting energy consumption as much as 70 percent by using the following strategies:

1. dimming
2. occupancy sensing
3. scheduling
4. daylight harvesting
5. task/ambient lighting
6. personal (manual) control of workstations

Although people can usually be relied on to turn lights on when it is too dark, they almost never turn lights off when they are not necessary. Consequently, to save energy, it is usually necessary to use automatic devices, such as occupancy sensors, photo sensors, timers, and remote switching equipment.

Occupancy sensors respond to people entering and leaving a room. In some situations a **vacancy sensor** is a better option, because it requires occupants to manually turn lights on and the sensor only turns the lights off. This type of sensor is especially appropriate for daylit spaces that need electric lighting only occasionally. They are based on either infrared or ultrasonic technology, each of which has advantages and disadvantages. Consequently, hybrid sensors that use both technologies have been developed.

Photo sensors respond to the availability of daylight. Most commonly, there is one sensor per room or zone, but lighting fixtures are now available with individual photo sensors.

Most **timers** are centrally located to turn lights on and off at a preset cycle. For example, they can turn the lights on just before people arrive at work and then turn them off when everybody has gone home. Centrally located timers are excellent whenever there is a regular schedule of activities. Timers can also be used for local control of lights. For example, many apartment houses and hotels in Europe have corridor timer-switches that turn lights on for about ten minutes, which is enough time to get to one's room or apartment. Thus, the corridor lights are on only when people use them. **Remote-control** switching enables people or a computer at a central location to control the lights. This central control of lights is part of what is now often called an **energy management system**. A computer using remote sensors and switches can be programmed to make efficient use of all energy used in a building.

Dimming is another powerful tool for the designer. Although halogen lamps can be dimmed very easily, dimming them makes them even more inefficient. Thus the dimming of halogen lamps should be used sparingly if at all. Fortunately, most discharge lamps can be dimmed, and fluorescent lamps can be dimmed at a reasonable cost. Most types of high intensity discharge lamps can now also be dimmed, but the special equipment required makes it somewhat more expensive. LEDs can be easily dimmed, but the dimmer must be carefully matched to the driver (power supply). When daylighting is used, switching and dimming are especially important, and were discussed in the previous chapter.

14.18 MAINTENANCE

The two main considerations in maintaining a lighting system are the aging of the lamps and the accumulation of dirt on the lamp and fixture.

Figure 14.18 shows light output as a function of time for a certain lamp. As the lamp ages, its lumen output depreciates until the lamp fails. However, some of the newer lamps like LEDs don't fail but keep getting dimmer and dimmer. Consequently, their life is defined as the time required for the lamp output to decline to 70 percent of the initial. The rate of decline and the length of life vary greatly with the specific lamp type, but the general pattern is the same for all. If a large **lamp lumen depreciation** is expected, the initial illumination level is increased to allow for the decline. If lamp life is short, lamp replacement must be made an easy operation. If replacement is difficult, a long-life lamp type should be chosen.

Light loss due to dirt accumulation is a separate problem. It is a function of the cleanliness of the work area and the design of the luminaire. For example, in dirty areas, such as a woodworking shop, indirect fixtures

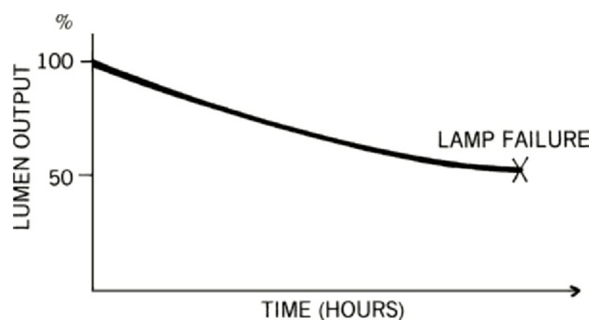


Figure 14.18 For traditional lamps, the lumen output typically declines over time until the lamp fails.

would not be appropriate because dirt accumulates mostly on the top side of lamps and fixtures. Manufacturers give information on how well their luminaires maintain light output under various levels of dirt accumulation. A **luminaire dirt depreciation** factor can be used to choose the right fixture for a specific environment. Nevertheless, periodic cleaning of lamps and luminaires is required even in clean areas. Thus, easy access for cleaning and relamping is an important design consideration.

14.19 RULES FOR ENERGY-EFFICIENT ELECTRIC LIGHTING DESIGN

With informed design and efficient equipment, high-quality lighting can be achieved with a power density below 1 watt per ft^2 (9.3 watts per m^2). This is remarkable when you consider that the norm in the 1980s was more than five times higher (Table 14.2). Use the following strategies to achieve a high-quality, energy-efficient lighting system.

Rules for the Design of Efficient Electric Lighting

1. Use light-colored surfaces whenever possible for ceilings, walls, floors, and furniture.
2. Use local or task lighting to prevent the unnecessary high illumination of nonwork areas.
3. Use task/ambient lighting for most work areas.
4. Use electric lighting to complement daylighting (see Chapter 13 for details).
5. Use the lowest recommended light level for electric lighting. For daylighting, however, the illumination can be set a little higher in the summer and can be much higher during the heating season.
6. Carefully control the direction of the light source to prevent glare and veiling reflections. A small amount of high-quality light can be more effective than a large amount of low-quality light.
7. Use high-efficacy lamps (e.g., metal halide, fluorescent, and LED).
8. Use efficient luminaires (e.g., avoid luminaires with black baffles and indirect fixtures in dirty areas).
9. Avoid light pollution and light trespass by using low levels of outdoor lighting, no uplighting, and special asymmetric luminaires to minimize projecting light where it is not wanted. Illuminate the exterior of buildings from the top down rather than from the bottom up, as is now standard practice.
10. Use the full potential of manual and automatic switching and dimming to save energy and the environment. Use occupancy sensors, photosensors, timers, and central energy-management systems whenever possible.
11. Use Energy Star–labeled lamps.

Many more specific suggestions for energy-conscious lighting are mentioned throughout the three chapters on lighting.

14.20 LAWS AND STANDARDS

Specifying efficient lamps is becoming easier because of laws prohibiting the most inefficient lamps. The United States has joined much of the world in getting inefficient lamps off the market. For example, the Energy Policy Act of 1992 and updated in 2005 phased out T12 fluorescent lamps and magnetic ballasts starting in 2012. Also, the Energy Independence and Security Act of 2007 (also known as the Clean Energy Act) has phased out 100 W and 75 W incandescent lamps and is currently phasing out 60 W and 40 W lamps.

There are also energy standards established to aid the designer in creating more sustainable buildings. One such standard is the Energy Star program jointly run by the Environmental Protection Agency (EPA) and Department of Energy (DOE). To carry the Energy Star label, products such as appliances, computers, lamps, and luminaires must meet elevated energy efficiency standards. Thus, a concerned lighting designer will specify only lamps and luminaires that carry the Energy Star label.

Whenever possible, specify high efficacy lamps with the GU-24 socket system to prevent their replacement with low-efficacy lamps (Fig. 14.20).

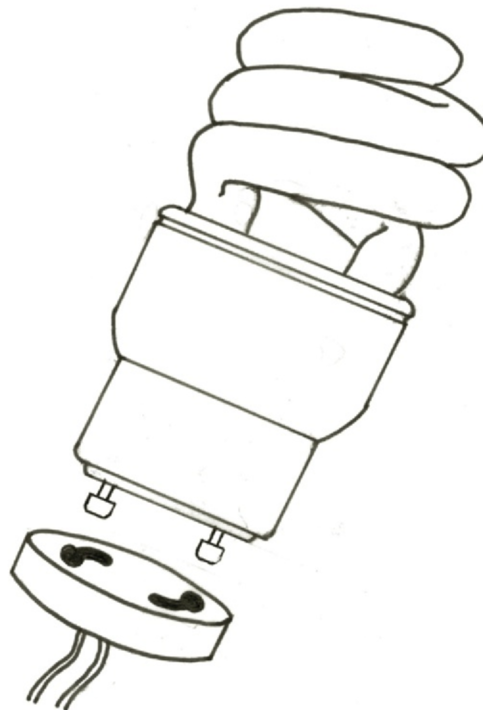


Figure 14.20 To prevent the accidental or intentional replacement of efficient lamps with less efficient lamps, specify lamps and sockets with connectors like the GU-24.

14.21 CONCLUSION

A good lighting design stresses flexibility and quality, not sheer quantity. It must satisfy biological as well as activity needs. In doing so, it must prevent direct glare, veiling reflections, and excessive brightness ratios. In addition, in a world of limited resources, good lighting must be accomplished with a minimum of waste. Inefficient lighting systems not only guzzle huge amounts of electrical energy directly, but they also add greatly to the air-conditioning load, which then requires more equipment and still more electrical energy. Every three watts of electric lighting generate another watt of mechanical cooling. Thus, every lighting watt reduction actually saves 1.33 watts (*Lighting Design Lab*, 2010). Good lighting design is critical for a more sustainable world.

KEY IDEAS OF CHAPTER 14

1. One of the most important characteristics of a lamp is its efficacy (lumens per watt).
2. Another important characteristic of lamps is the color-rendering properties of the emitted light (i.e., its CRI and Kelvin temperature.
3. Incandescent lamps are obsolete for general illumination (even in homes). Use them only for special small-scale applications.
4. Compact fluorescent lamps are a good substitute for most incandescent-lamp applications.
5. Halogen lamps should be used only where beam control is vital (e.g., highlighting small objects). Whenever possible, use the much more efficient ceramic metal halide lamps or LED lamps.
6. Use fluorescent or metal halide lamps for general illumination where color rendition is important.
7. Use HPS lamps where efficacy is more important than color rendition.
8. Task/ambient lighting offers both high-efficiency and high-quality lighting.
9. The illumination from a point light source is inversely proportional to the square of the distance.
10. The illumination from a linear light source is inversely proportional to the distance.
11. The illumination from an infinite-area light source does not vary with distance.
12. Avoid light pollution and light trespass for a healthier, more sustainable, and more beautiful world.
13. Use automatic controls, such as occupancy sensors, photocells, and timers, to eliminate waste.
14. Use lamps certified by the Energy Star program.

Resources

FURTHER READING

(See the Bibliograpy in the back of the book for full citations.)

Brown, G. Z., and M. Dekay. *Sun, Wind, and Light: Architectural Design Strategies*, 3rd ed.

Cuttle, C. *Lighting by Design*.

Egan, M. D., and V. Olgyay. *Architectural Lighting*, 2nd ed.

Flynn, J. E., J. A. Kremers, A. W. Segil, G. Steffy. *Architectural Interior Systems: Lighting, Acoustics, Air Conditioning*, 3rd ed.

Futagawa, Y., ed. *Light and Space: Modern Architecture*.

Gordon, G., and J. L. Nuckolls. *Interior Lighting for Designers*, 4th ed.

Grondzik, W., and A. G. Kwok. *Mechanical and Electrical Equipment for Buildings*, 12th ed.

Grosslight, J. *Lighting Kitchens and Baths*.

———. *Light, Light, Light: Effective Use of Daylight and Electric Lighting in Residential and Commercial Spaces*, 3rd ed.

IESNA Lighting Handbook.

Ishii, M. *Lighting Horizons*.

Karlen, M., and J. Benya. *Lighting Design Basics*.

Kwok, A. G., and W. T. Grondzik. The *Green Studio Handbook: Environmental Strategies for Schematic Design*.

Lam, W. M. C. *Perception and Lighting as Formgivers for Architecture*.

Leslie, R. P., and K. M. Conway. *The Lighting Pattern Book for Homes*.

Leslie, R. P., and P. A. Rodgers. *The Outdoor Lighting Pattern Book*.

Millet, M. S. *Light Revealing Architecture*.

Neumann, *D. Architecture of the Night: The Illuminated Building*.

Schiler, M. *Simplified Design of Building Lighting*.

Steffy, G. R. *Architectural Lighting Design*, 2nd ed.

———. *Time-Saver Standards for Architectural Lighting*.

Trost, J. *Electrical and Lighting*.

ORGANIZATIONS

(See Appendix K for full citations.)

California Lighting Technology Center
www.cltc.ucdavis.edu

IESNA Illuminating Engineering Society of North America
www.iesna.org

International Association of Lighting Designers (IALD)
www.iald.org

Lawrence Berkeley National Laboratory (LBNL)
www.eande.lbl.gov

Lighting Design Lab
www.northwestlighting.com

Lighting Research Center at RPI
www.lrc.rpi.edu

National Lighting Bureau
www.nlb.org

CHAPTER 15

THE THERMAL ENVELOPE: KEEPING WARM AND STAYING COOL

Waste not, want not, is a maxim I would teach.
Let your watchword be dispatch, and practice what you preach.
Do not let your chances like sunbeams pass you by.
For you never miss the water till the well runs dry.
Rowland Howard, 1876

Reducing the size of the mechanical equipment is not
just a free lunch, but one they prepay you to eat.
Amory Lovins, Rocky Mountain Institute

15.1 BACKGROUND

This chapter discusses the creation of an efficient thermal envelope to minimize the heat loss in winter and heat gain in the summer. The design of a tight thermal envelope is the first tier of the three-tier design approach to heating and cooling a building (Fig. 15.1a).

Suppose we wanted to keep a certain bucket full of water. Our common sense would have us repair the leaks, at least the major ones, rather than just refilling the bucket continuously. Yet with regard to energy, we usually keep a leaky building warm by pouring in more heat rather than patching the leaks (Fig. 15.1b).

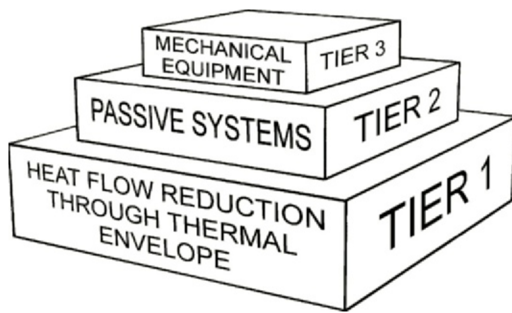


Figure 15.1a The best and most sustainable way to heat and cool a building is to use the three-tier design approach. This chapter covers strategies in tier one.



Figure 15.1b If we could see heat flowing out of a building as we see water leaking from a container, then our attitudes might be different.

Perhaps if we could see the energy leaking out, we would plug the leaks. Fortunately, we can see the holes in the thermal envelope with thermography, and it is very effective in convincing people to upgrade their buildings. In a thermogram of the exterior of a building, hot and cold areas are shown in different shades of gray or colors (Fig. 15.1c and Colorplates 5 and 6). A thermogram of the author (Fig. 15.1d) proves that he is not hotheaded.

President Jimmy Carter and President Ronald Reagan did not always agree, but they did agree that conservation implied a reduction of comfort. They were both wrong. From experience, we now know that comfort can be increased if the proper conservation techniques are used. For example, indoor comfort increases dramatically when insulation is added to the walls, the ceiling, and especially the windows. When the author moved into his present home, he was uncomfortably cold even when the thermostat was set at 80°F (27°C). The addition of ceiling insulation and insulating drapes over the windows now allows a thermostat setting of 70°F (21°C) to provide complete thermal comfort. Thus, insulation not only reduced energy consumption,

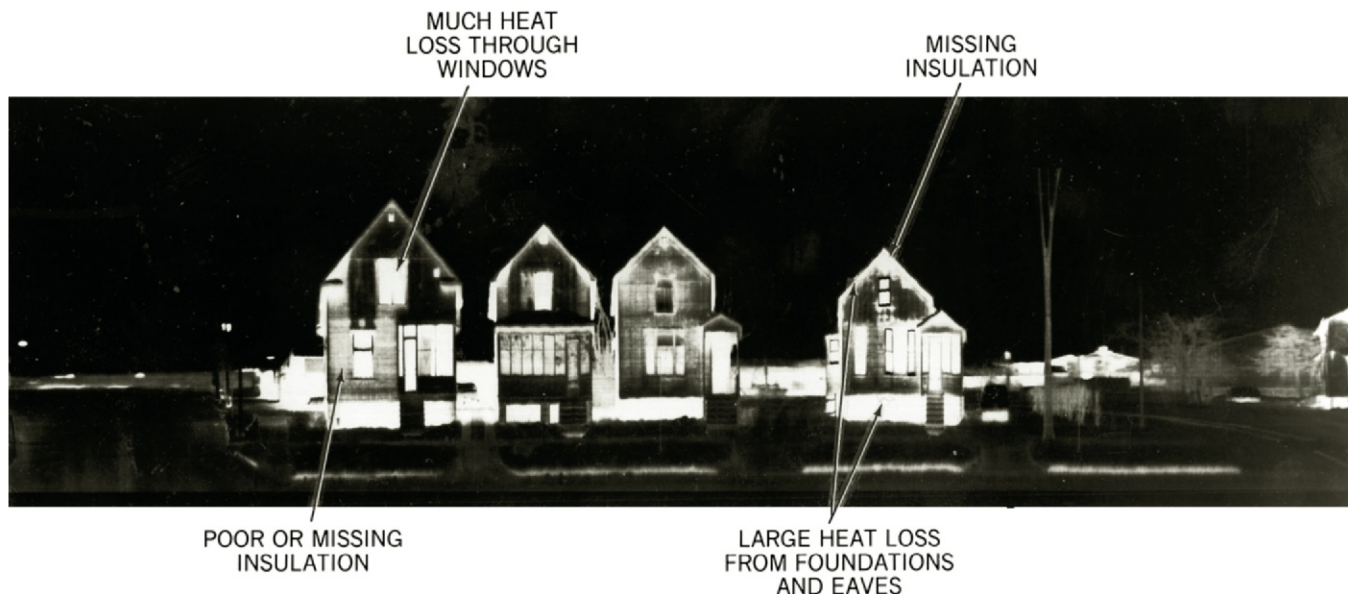


Figure 15.1c Thermography can pinpoint the weakness in the thermal envelope. This winter thermogram indicates the warmest areas, which are a result of the greatest heat loss. (Vanscan [Thermogram] by Daedalus Enterprises, Inc.)

it also increased thermal comfort by increasing the mean radiant temperature of the space (see Figure 3.12).

Because conservation has such a negative connotation, it is better to talk of energy efficiency. It is not only possible but also more likely to have a higher standard of living through energy efficiency. After all, higher efficiency will enable us to meet the needs of heating, cooling, and lighting at less cost, leaving more money for other needs.

Making adjustments to new thermal realities has a long history in America. The early settlers in New England found that the wattle-and-daub construction method that they had brought from England was inappropriate in the harsh climate of the Northeast (Figure 15.1e). They quickly burnt and exhausted the local wood supply in trying to stay warm. Because bringing wood from great distances was expensive, they modified their building method and switched to clapboard siding for tighter construction and greater comfort. Although this was a great improvement in keeping the cold out, it was not as good as the log cabin technology that was brought to the United States later by Swedish immigrants. Compared to the alternatives available in those days, the thick logs were good insulation, but the numerous joints were still a significant source of infiltration. It was the invention of that underappreciated material tar paper that really cut down on infiltration. By today's standards, wood is also a poor insulator. Today, controlling heat flow is not so much a technical problem as one of economics and concern for the planet.



Figure 15.1d Thermogram of the author—a good likeness, as is Colorplate 35.



Figure 15.1e The traditional wattle-and-daub construction, so popular in old England, was unacceptable in the harsh climate of America. There was little insulation to counter heat flow, and infiltration was a major problem, as can be seen from the cracks in this demonstration wall.

15.2 HEAT LOSS

Heat is lost from a building by transmission, infiltration, and ventilation (Fig. 15.2a). Heat is lost by transmission through the ceilings, walls, floors, windows, and doors. Heat flow by transmission occurs by a combination of conduction, convection, and radiation. The proportion of each depends mainly on the particular construction system (Fig. 15.2b).

The magnitude of the heat loss rate through a building's skin is a function of the area, the temperature difference between the indoors and outdoors, and the thermal resistance of the skin (see Sidebox 15.2A). Thus, the heat loss can be minimized by the use of a compact design (minimum area), common or party walls (no temperature difference across walls), and plenty of insulation (large thermal resistance).

Heat is also lost by the infiltration of cold air through joints in the construction, as well as through cracks around windows and doors. The heat loss due to infiltration is a function of the rate of cold air entering the building and the temperature difference between the indoor and outdoor air. The amount of cold air that infiltrates on the windward side of the building is equal to the amount of hot air that leaves on the leeward side. Thus, counting both the air entering and leaving is an error

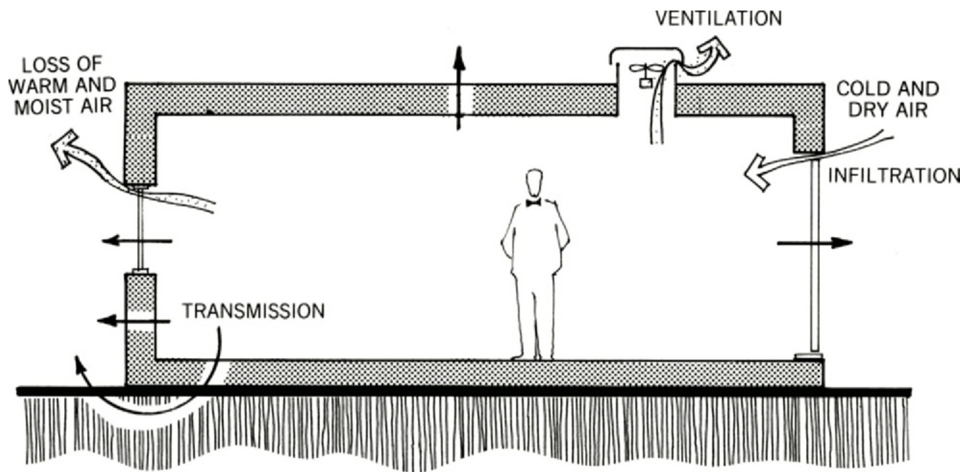


Figure 15.2a Heat is lost from a building by transmission, infiltration, and ventilation.

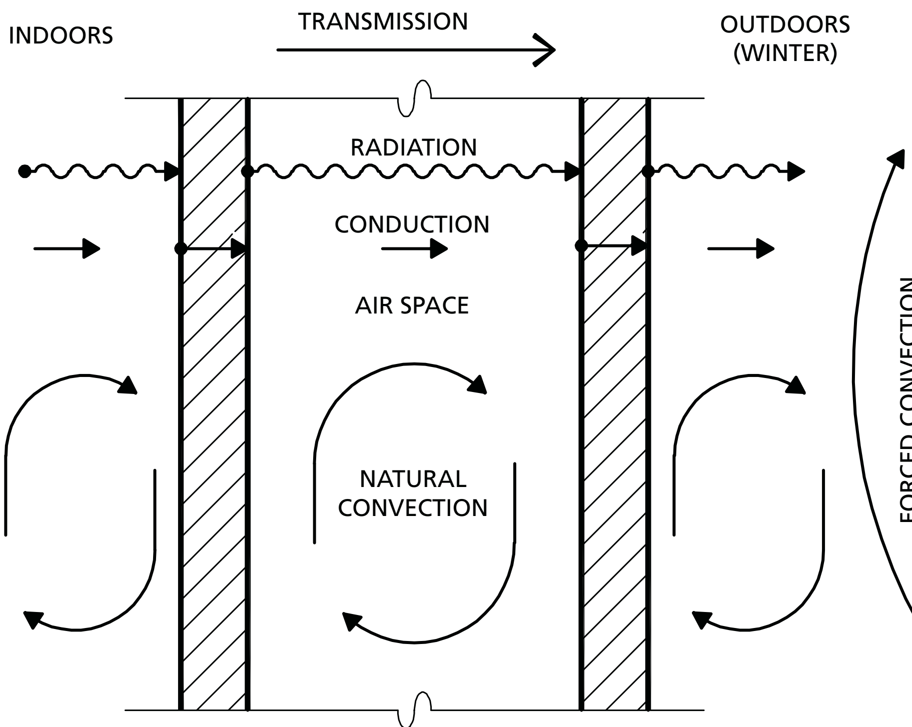


Figure 15.2b Heat flow by transmission consists of a combination of conduction, convection, and radiation. Winter heat loss is shown in this schematic wall detail consisting of two plywood layers separated by an air space created by the studs.

comparable to counting both heads and tails to determine the number of coins. Sidebox 15.2B shows how infiltration heat loss is calculated by the air-change method. A more complicated method uses the length of cracks at windows and doors. It is called the crack method, and although it is more accurate, the results are still rough approximations. However, the tightness of an existing building can be accurately determined by a blower-door test, which is explained in Section 15.13. If the indoor air is being humidified, latent as well as sensible heat will be lost by infiltration in the winter.

Heat loss due to ventilation is very much like infiltration except that it is a controlled and purposeful form of air exchange. Fortunately, heat-recovery devices, as described in Section 16.18, can save as much as 90 percent of the heat, both sensible and latent, that would otherwise be lost due to ventilation.

SIDEBOX 15.2A

Heat Loss Due to Transmission Through Walls, Windows, Doors, and Roofs

$$\text{Heat loss by transmission} = \frac{(\text{area}) \times (\text{temperature difference})}{(\text{total thermal resistance})}$$

$$HL = \frac{A \times (T_i - T_o)}{R_T}$$

or the more conventional but not as conceptually clear format:

$$HL = A \times U \times (T_i - T_o)$$

$$\text{since } U = \frac{1}{R_T} \text{ (see Section 3.17)}$$

where U is the heat-flow coefficient and where:

	I-P	SI
HL is the rate of heat loss	Btu/h	watts
A is the area	ft^2	m^2
T_i is the indoor design temperature	°F	°C
T_o is the outdoor design temperature	°F	°C
R_T is the total resistance	$\frac{(\text{ft}^2)(°\text{F})}{\text{Btu/h}}$	$\frac{(\text{m}^2)(°\text{C})}{\text{W}}$

I-P Example: What is the heat loss per hour through an 8 ft high and 20 ft long wall that has a total thermal resistance of 16 (R-value) if the indoor design temperature is 75°F and the outdoor design temperature is 20°F?

$$HL = \frac{(A) \times (T_i - T_o)}{R} = \frac{(20)(8)(75 - 20)}{16} = 550 \text{ Btu/h}$$

SI Example: What is the heat loss of a 3 m high and 7 m long wall that has a thermal resistance of RSI-4, if the indoor design temperature is 20°C and the outdoor design temperature is minus 10°C?

$$HL = \frac{(A) \times (T_i - T_o)}{R_T} = \frac{(3)(7)(20 - (-10))}{4} = 157.5 \text{ watts}$$

SIDEBOX 15.2B

Heat Loss Due to Infiltration by the Air-Change Method

Heat loss per hour by infiltration
= *(constant)* × *(air changes per hour)* × *(volume)* × $(T_i - T_o)$

In I-P:

$$HL = (0.018) \times (ACH) \times (V) \times (T_i - T_o)$$

In SI:

$$HL = (0.005) \times (ACH) \times (V) \times (T_i - T_o)$$

Where:

	I-P	SI
HL is the heat loss rate	Btu/h	watts
ACH* is the air changes per hour	No units	No units
V is the volume	ft^3	m^3
T_i is the indoor design temperature	°F	°C
T_o is the outdoor design temperature	°F	°C

*In winter, use 0.5, 0.85, and 1.3 ACH, respectively, for tight, medium, and loose modern construction. In summer, use 70 percent of the winter values.

15.3 HEAT GAIN

Although heat gain in a building is similar to heat loss, some significant differences exist. Similar to winter, there is heat gain by transmission, infiltration, and ventilation. However, unlike winter, there is also heat gain due to internal heat sources, the insulating effect of thermal mass, and, of course, the action of the sun (Fig. 15.3).

Depending on the building type, the internal heat sources can be either a major or a minor load. Internally dominated buildings are those that have a large amount of heat generated by people, lights, and appliances. The heat can be in both sensible and latent (water-vapor) form.

Thermal mass can reduce the heat gain when temperatures are fluctuating widely during a day. The insulating effect is most pronounced when the daily temperature range varies from above to below the comfort zone, a situation found in hot and dry climates. (This effect was explained in Section 3.19 and will be explained further in Section 15.11.)

Infiltration is generally less of a problem in the summer than in the winter because of the lower wind velocities. Instead, ventilation is often a major source of heat gain. This is

especially true in humid climates because of the large latent-heat component of the air. The same heat-recovery devices mentioned above for reducing heat loss can also be used to reduce both sensible and latent heat gain when ventilation brings in hot, humid summer air. Ventilation and heat-recovery devices are explained more fully in Section 16.18.

The part of the heat gain due to the temperature difference across a window is calculated the same way as heat loss in winter. Of course, summer indoor and outdoor design temperatures are used. However, the heat gain due to solar radiation through the glazing is calculated as shown in Sidebox 15.3A.

The heat gain calculation through the opaque parts of the thermal envelope (walls, roof, and doors) is similar to that for heat loss except for the extra impact of the sun heating the outdoor surfaces. The darker the color, the greater the heat gain, because dark colors absorb a large amount of solar radiation and get quite hot. This results in a higher temperature differential between indoors and outdoors than can be accounted for by the actual outdoor-air temperature. This larger temperature differential is called the sol-air temperature. When the insulating effect of thermal mass is also included, the temperature differential used is called the design-equivalent temperature difference. Sidebox 15.3B illustrates how to calculate heat gain through the opaque parts of the building envelope.

Since sol-air temperatures are much lower with light-colored surfaces than with dark-colored surfaces, one of the most effective and certainly least expensive ways to reduce heat gain is to specify light-colored building finishes.

SIDEBOX 15.3A

Heat Gain Due to Solar Gain Through Glazing

The rate of solar heat gain through glazing = (*area*) × (*solar heat gain factor*) × (*solar heat gain coefficient*)

$$HG = (A) \times (SHGF) \times SHGC$$

Where

	I-P	***SI***
HG is the rate of solar heat gain through glazing	Btu/h	watts
A is the actual glazing area	ft^2	m^2
*SHGF** is the unit solar heat gain	Btu/h per ft^2	W/m^2
SHGC† is the solar heat gain coefficient	no units	no units

IP Example: What is the solar heat gain per hour through a clear 4 × 5 ft double glazed-window that is 80 percent glass and 20 percent frame? The window is at 40°N latitude and faces south. It is 11 A.M. on March 21.
Where

$HG = (A) \times (SHGF) \times (SHGC)$
A (of glazing) $= (4 \times 5)(0.8) \times 16\ ft^2$
$SHGF$ from *ASHARE Handbook* $= \frac{197\ Btu/h}{ft^2}$
$SHGC$ (from Table 9.20) $= 0.73$

Therefore

$$HG = (16)(197)(0.73) = 2301\ Btu/h$$

SI Example: What is the solar heat gain rate through a clear 1 m × 2 m double-glazed window that is 80 percent glass and 20 percent frame? The window is at 40°N latitude and faces south. It is 11 A.M. on March 21.
Where

$HG = (A) \times (SHGF) \times (SHGC)$
$SHGF$ from *ASHRAE Handbook* $= 622\ W/m^2$
$= (1)(2)(0.8)(622)(0.73)$
$= 726$ watts

*The solar heat gain factor SHGF is a function of latitude and orientation of glazing, time of year, and time of day. Values can be found in the *ASHRAE Handbook of Fundamentals*.
†The solar heat gain coefficient SHGC quantifies the amount of shading due to glazing type, trees, shading devices, etc. See Table 9.20 for values.

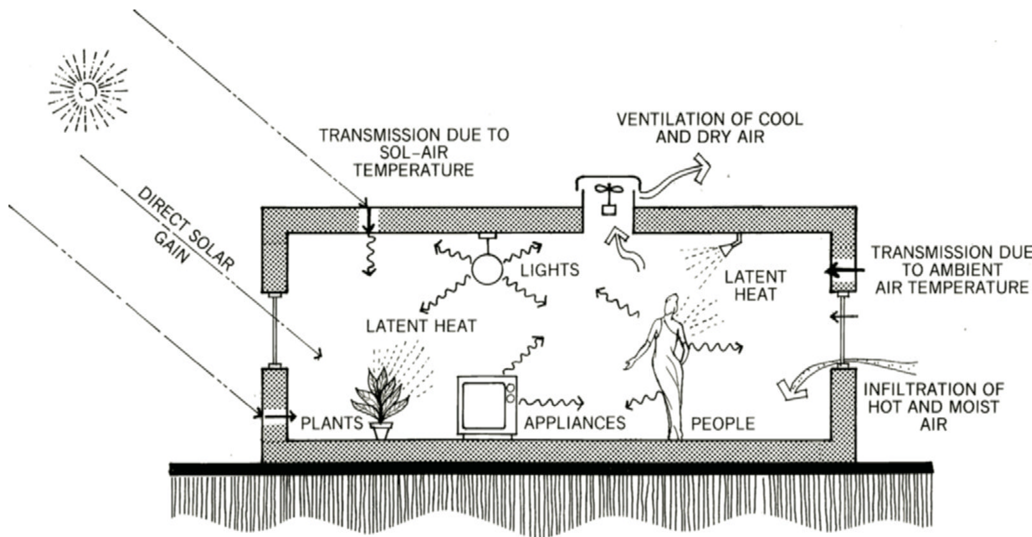


Figure 15.3 Sources of sensible and latent heat gain.

SIDEBOX 15.3B

Heat Gain Through Walls and Roofs

$$HG = \frac{(A) \times (DETD)}{R_T} \quad \text{or} \quad (A) \times (U) \times (DETD)$$

where

	I-P	SI
HG is the rate of heat gain	Btu/h	watts
$DETD$ is the design-equivalent temperature difference†	°F	°C
R_T is the total resistance of the wall or roof structure	$\frac{(ft^2)(°F)}{Btu/h}$	$\frac{(m^2)(°C)}{W}$
U	$1/R_T$	$1/R_T$

†*DETD* is a function not only of the temperature difference across the building envelope but also of the thermal mass and the color of the outdoor surface.

15.4 SOLAR REFLECTIVITY (ALBEDO)

The heat gain through a white roof will be about 50 percent of that of a black roof. The measure of a surface's reflectivity of solar radiation is called albedo. It varies from 0 percent to 100 percent, where a surface with an albedo of 0 percent would absorb all solar radiation and an albedo of 100 percent would reflect all solar radiation. See Table 15.4 for albedo values of typical building surfaces.

Studies have shown that the total air-conditioning in many buildings can be reduced by 20 percent just by changing the albedo of the roof and walls from a typical medium-dark value of 30 percent to a light-colored value of 90 percent. During initial design and construction there is usually no cost penalty for choosing light colors, but the savings go on for the life of the material.

Although polished metal surfaces have high reflectivity (albedo), they have low emissivity and, therefore, get much warmer than surfaces with light colors, which have a high emissivity (see again Section 3.11). Clearly then, light colors should be used in hot climates. In dense urban areas, the paving and other surfaces between buildings should also have a high albedo. Researchers have found that in a typical American city, the value of the albedo can be realistically raised by about 15 percent, and this increase in reflectivity will result in a drop of a city's temperature of about 5°F (3°C). In such a city, a light-colored building will benefit both from less heat gain from direct solar radiation and because the outdoor-air temperature will be lower. It should be stressed that although grass and trees have a low albedo, they do not heat a building or city. Transpiration from plants more than offsets the absorption due to their dark color.

It should be relatively easy to convince people to use light colors in hot climates. Light colors not only save money, energy, and the environment, but they are also traditional in hot climates. Yet for some unknown reason, many people are convinced that black roofs are beautiful and white roofs are ugly. After being shown the picture of the buildings in Colorplates 31 and 33, most people admit that white roofs are not ugly. They then argue that white roofs can't be used because they get dirty. However, the author has found that smooth white metal roofs get no more stained than black shingle roofs.

Table 15.4 Albedo of Typical Building Surfaces

Building Surface	% Albedo*
White paint	50–90
Highly reflective roof†	60–70
Colored paint	10–40
Brick and stone	10–40
Concrete	10–40
Red/brown tile roof	10–40
Grass	20–30
Trees	10–20
Corrugated roof	10–20
Tar and gravel roof	5–20
Asphalt paving	5–20

*Albedo describes the reflectivity of the total solar spectrum (ultraviolet, visible, and infrared), while the reflectance factor (RF) only describes the reflectivity of light. Values from Akbari et al., eds., *Cooling Our Communities* (1992).
†A white roof with some dirt accumulation

15.5 COMPACTNESS, EXPOSED AREA, AND THERMAL PLANNING

Compactness

Until the advent of modern architecture, buildings generally consisted of simple volumes richly decorated. Modern architecture changed that situation and created buildings of complex volumes simply decorated. Unfortunately, complex volumes usually result in large surface-area-to-volume ratios. For example, the compact cube and the spread-out alternative in Figure 15.5a have the same volume, yet the surface area of the spread-out volume is 60 percent greater than that of the cube. In most cases, a building with more surface area requires more resources of every kind for both construction and operation. As was mentioned in the sections above, heat gain and heat loss are directly proportional to surface area. Throughout history, compact buildings were built not just for the poor and the frugal middle class but also for the rich and powerful (Fig. 15.5b).

In extreme climates, building compactness was also extreme. Because the sphere has the least surface area to volume, the igloo is the ideal form for living in the frigid Arctic regions, and the cylindrical domed yurt of windy cold Mongolia is almost as compact (Fig. 15.5c).

A note of caution is in order here because we can easily learn the wrong lessons from the past. For example, our image of a traditional home is one with many wings. This can be a misleading prototype because authentic old homes almost always started out as compact designs. It was only after many generations of additions that the quaint nostalgic image we have today emerged (Fig. 15.5d).

There are some exceptions to the rule that compact designs are more sustainable. When natural ventilation and not air-conditioning is the dominant cooling strategy and the climate has mild winters, an open, spread-out plan might be best. If daylighting in a large multistory building has a high priority, a more spread-out plan might also be in order. The glass-covered atrium

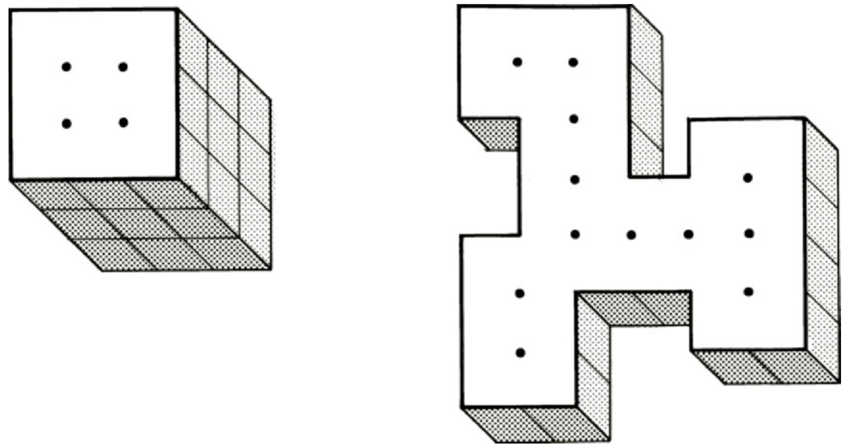


Figure 15.5a Although the volumes are equal, the less compact form (right) has 60 percent more surface area and therefore 60 percent more heat gain and heat loss.



Figure 15.5b Like most mansions of the past, the Andrew Carnegie Mansion on Fifth Avenue in New York City is a spacious and ornate yet compact building.



Figure 15.5c For many reasons, especially compactness, the yurt is an ideal building form for cold, windy Mongolia.

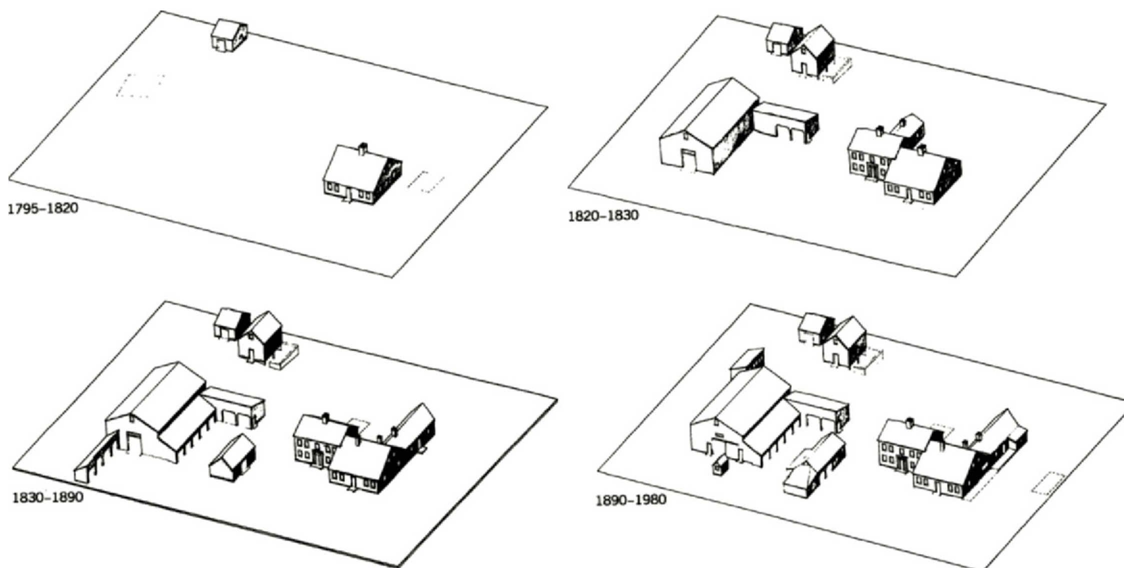


Figure 15.5d Evolution of the Nutting Farm. Note especially the changes in the residence from compact to spread out. (Reproduced from *Big House, Little House, Back House, Barn* by Thomas C. Hubka, by permission of the University Press of New England. Copyright 1984, 1985, 1987 by Trustees of Dartmouth College.)

is usually the result of a simultaneous desire for more surface area for daylighting and less surface area for heating and cooling needs (see Fig. 13.9e).

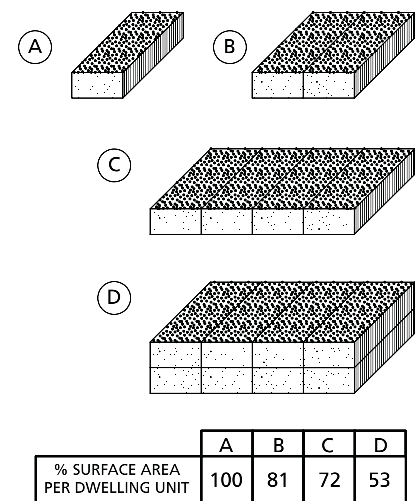
Exposure

Ultimately, what counts is not total surface but exposed surface. Through the sharing of walls, great savings in heating and cooling are possible. For example, row housing of four attached units has about 30 percent less surface area than four detached units, and when eight units are combined as shown in Figure 15.5e, the exposed surface area is decreased about 50 percent.

Exposure can also be reduced by the arrangement of the floor plan for thermal planning. Spaces that require or tolerate cooler temperatures should be placed on the north side of the building. Buffer spaces, such as garages, should be on the north to protect against the cold or on the west to protect against summer heat.

Thermal Planning

Solar thermal conditions around a building are shown for both summer



	A	B	C	D
% SURFACE AREA PER DWELLING UNIT	100	81	72	53

Figure 15.5e By sharing walls, attached units can significantly reduce the amount of exposed surface area.

and winter in Figure 15.5f. A bubble diagram for a residence based on the solar/thermal conditions is shown in Figure 15.5g. The kitchen would be on the northeast because it needs little heat, while the breakfast area would be on the southeast to receive morning sun all year. The utility and garage areas would be on the northwest to buffer against the winter cold and summer heat. Bedrooms are on the north because they are used little during the day and a cool room is better for sleeping.

A plan based on this diagram would be in harmony with our circadian rhythms, thereby promoting both physical and mental well-being (Fig. 15.5h). Consider preparing and eating breakfast with bright, cheerful sunlight. You would spend the day in the family room with warm south lighting, and at night you would sleep in the pleasantly cool bedrooms on the north.

Another example of solar/thermal planning is the bubble diagram for a K–12 school (Fig. 15.5i). The classrooms face southeast for year-round warm south lighting from early morning until early afternoon, while the gymnasium is on the north because it needs to be the coolest space.

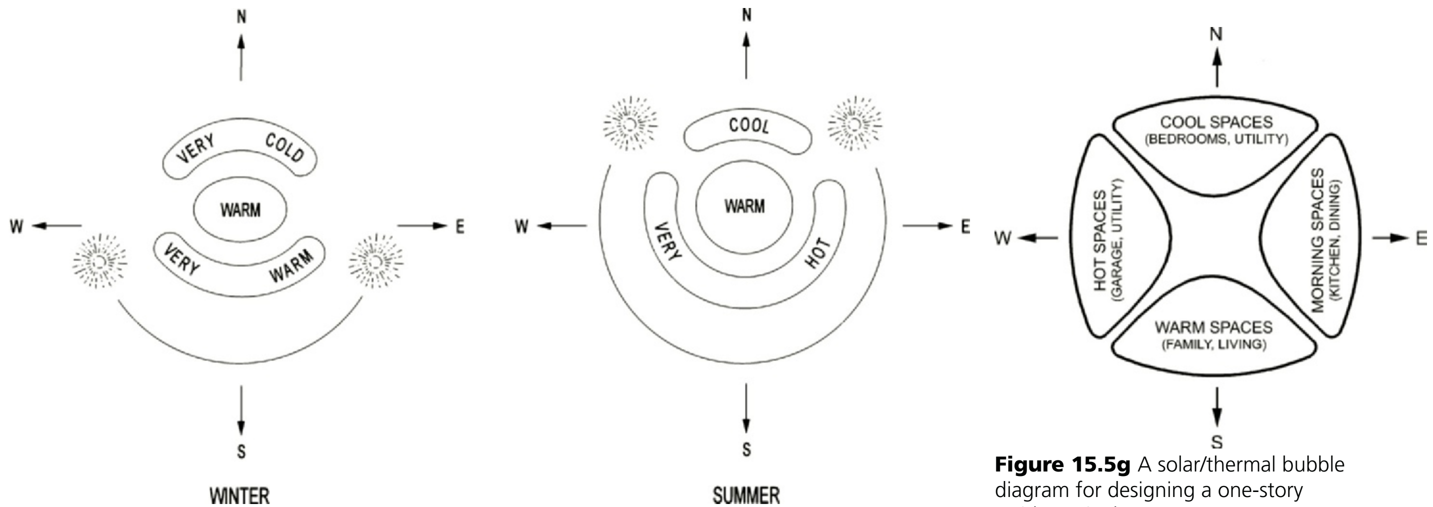


Figure 15.5f A solar/thermal zoning pattern for winter and summer is shown.

Figure 15.5g A solar/thermal bubble diagram for designing a one-story residence is shown.

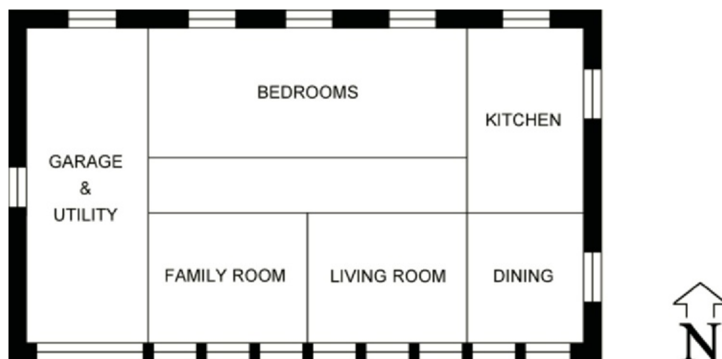


Figure 15.5h A conceptual plan for a one-story residence based on solar/thermal planning considerations is shown.

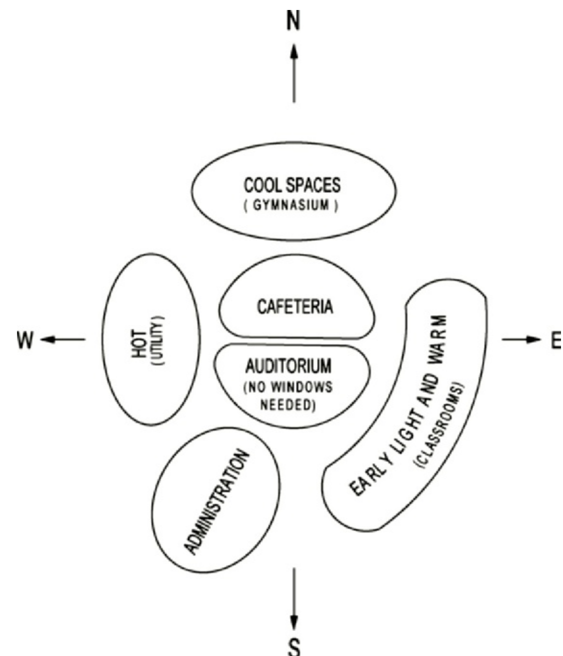


Figure 15.5i A solar/thermal bubble diagram for a K–12 school is shown.

15.6 INSULATION MATERIALS

Fifty years ago, many buildings were still built without insulation in the walls. As a consequence of the energy crisis of 1973, the question is no longer whether insulation should be used but rather which material and how much.

In general, "the more insulation the better" is a good principle to start with. The benefits and good characteristics of insulation include the following:

1. Saving energy both summer and winter and therefore saving the environment.
2. Saving money by saving energy, and the insulation is relatively inexpensive.
3. Increasing thermal comfort by raising the mean radiant temperature (MRT).
4. It is a very durable and long-lasting material
5. It is much easier to install during initial construction than to add later when its need becomes obvious.

There is, of course, a limit to how much should be used. The law of diminishing returns says that every time you double the amount of insulation, you cut the heat loss in half. This is great the first few times as the heat loss goes from 1 to $1/2$ to $1/4$, etc. Unfortunately, the cost keeps up with the thickness of insulation, while the heat loss decreases by ever smaller amounts (e.g., from $1/32$ to $1/64$ to $1/128$, etc.). However, this simplistic approach to building economics has done much damage. A more realistic approach is to see how the cost of the whole building changes as more insulation is used. As Amory Lovins says, "You can tunnel through the cost barrier." As more insulation is used, the mechanical heating and cooling systems get smaller and less expensive. In many climates, superinsulation can eliminate the heating system altogether, and in some climates it also eliminates the cooling system. Thus, large amounts of insulation can be less expensive than small amounts even for the initial costs.

Large amounts of insulation also provide a passive security system. When there is a power failure in the winter in a superinsulated building, the temperature indoors will drop less, and more slowly, than in a conventional building. It is surprising that in a world where people crave security, they don't make their homes more secure. However, there is growing interest in making our buildings and communities more resilient by the way they are designed and built. Furthermore, since future energy supplies and cost are uncertain, it is wise to be conservative and to use as much insulation as possible.

Insulation is forever—diamonds are often stolen!

Table 15.6A gives recommended insulation levels. These values and those required by codes should be considered minimum values. Consider that superinsulated buildings, which are gaining in popularity, use about twice these levels. The main obstacle to using high levels of insulation is not so much the cost of the insulation as the need to change construction details to allow the use of thicker insulating materials.

The bar chart of Figure 15.6a compares various insulating materials to each other and to common building materials by showing the thermal resistance of 1 in. (1 m) thick samples. Thus, it is easy to determine how many inches of insulation are required to achieve the R-value desired. Obviously, the materials with a high R-value per inch will result in a thinner wall or roof system.

Other important characteristics of insulating materials are moisture resistance, fire resistance, potential

Table 15.6A Recommended Insulation Levels in R-Value

Zone	Attic	Cathedral ceiling	Wall	Insulating sheathing	Floor
1	30–49	22–38	13–15	None	13
2	30–60	22–38	13–15	None	19–25
3	30–60	22–38	13–15	2.5–5	25
4	38–60	30–38	13–15	5–6	25–30
5	38–60	30–60	13–21	5–6	25–30
6	49–60	30–60	13–21	5–6	25–30
7	49–60	30–60	13–21	5–6	25–30

Notes:
1. These values are from the U.S. Department of Energy for wood-framed houses.
2. For RSI values, multiply by 0.17.
3. Use zone 7 for Alaska.
4. Use zone 1 for Hawaii, Guam, Puerto Rico, and the Virgin Islands.

for generating toxic smoke, physical strength, and stability over time. Table 15.6B summarizes the important characteristics of common insulation materials. Although all tables and figures in this book give both I-P and SI values, use Table 15.6C to convert R-values and U-coefficients for items not given.

Most insulation materials used in buildings fit into one of the following five categories: blankets, loose fill, foamed-in-place, boards, and radiant barriers. Most insulating materials work by creating miniature air spaces. The main exception is reflective insulation, which uses larger air spaces faced with foil on one or both sides to create a radiation barrier. Another insulating system that does not use

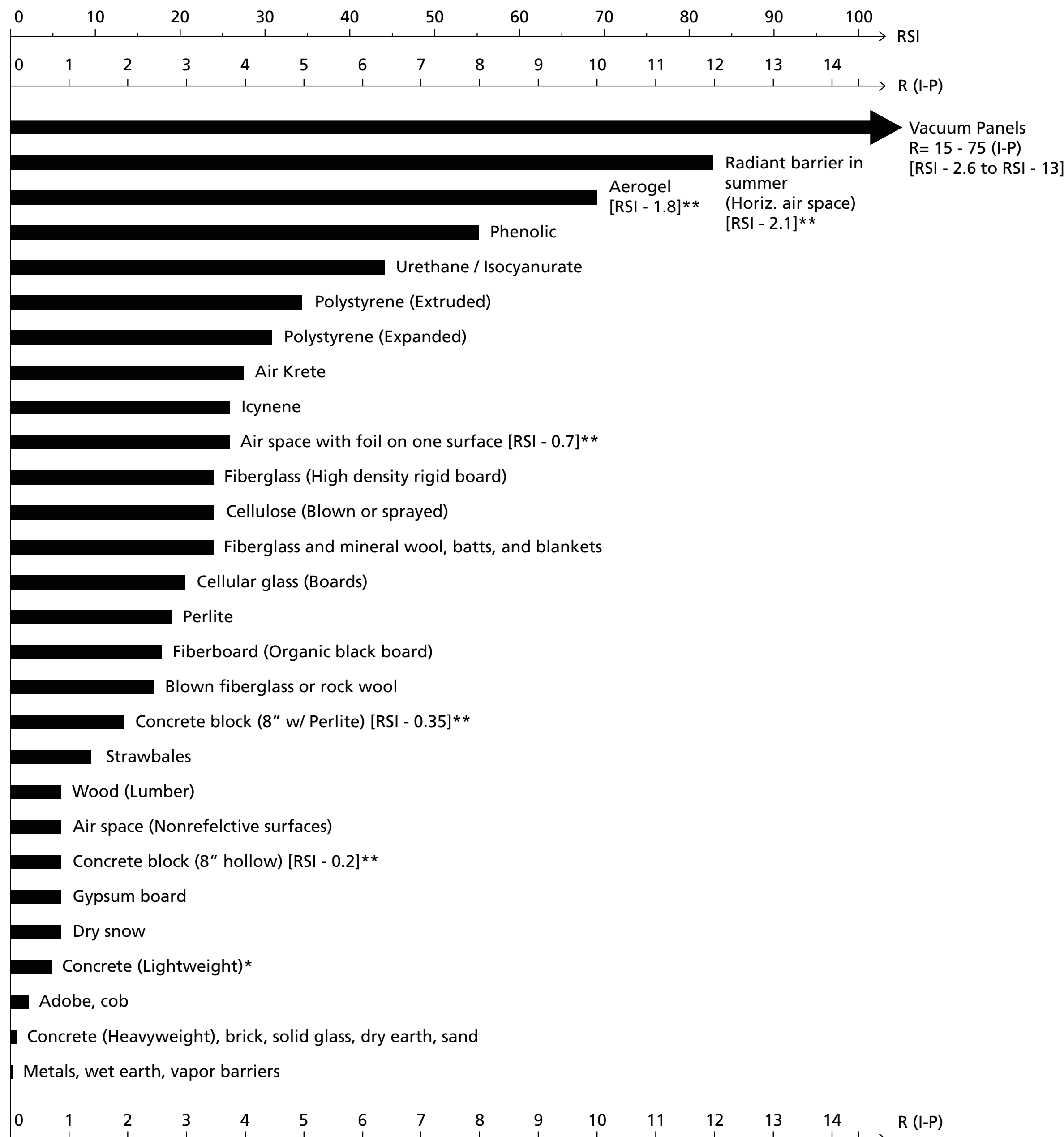


Figure 15.6a A comparison of the thermal resistance of various materials. All values are for 1 in. (1 m) thick samples, unless otherwise indicated. The actual resistance of a sample varies with density, temperature, material composition and, in some cases, moisture content.
*The resistance of lightweight concrete varies greatly with density and aggregate used, with R-values varying from 0.2 to 2.0 (RSI-1.4 to RSI-14).
**Not per inch (meter) but for actual thickness of block or air space.

Table 15.6B Insulation Materials

Material	Physical Format	Resistance R (I–P)*	RSI†	Comments
Fiberglass and rockwool	Batts	3–4	21–28	Good fire resistance
	Loose fill	2.2–3	15–21	Hard to completely fill air spaces
	Boards	3–4	21–28	Moisture reduces R-value
				Health danger to installers
				Use formaldehyde-free types
Perlite	Loose fill	2.5–3.3	17–23	Very inert volcanic rock
				Some dust
				Very fire resistant
Cellulose	Loose fill or sprayed	3.2–3.7	22–26	Made from recycled newspaper treated with borates
				Environmentally safe
				Easy to fully fill air spaces
				Must be kept dry
Cotton	Batts	3.0–3.7	21–26	Made from cotton and polyester mill scraps
				Very sustainable
"Icynene"	Spray-in	3.6	25	Plastic foam using water as foaming agent
				No off-gassing
				Sustainable
				Provides air sealing
"Air Krete"	Spray-in	3.9	27	All-mineral content
				Inert
				Very fire resistant
				Sustainable
				Remains friable
Expanded polystyrene (EPS)	Boards	3.6–4.2	25–29	Plastic foam
				Water resistant
				Must be protected from fire
Extruded polystyrene (XPS)	Boards	4.5–5	31–35	Plastic foam
				Very water resistant
				Must be protected from fire
				Can be used below grade
Polyiso cyanurate	Boards	5.6–6.3	39–44	Plastic foam
				Must be protected from water and fire
				Some off-gassing
				Very good sheathing material
Polyiso cyanurate with foil facing	Boards	7	49	Like regular polyisocyanurate, but has a higher R-value because there is no off-gassing
Urethane	Spray-in	3.6–6.8	25–47	Plastic foam
				R-value is a function of density
				Must be protected from fire
				Provides air sealing
				Forms a skin that is water resistant
Phenolic foam	Boards	8.2	57	Plastic foam
				Fire and water resistant
				Very low off-gassing
				Good structural strength
Aerogel	Blanket	10	70	Silica foam
				Fire and water resistant
				Good for reducing heat bridges

(*Continued*)

Material	Physical Format	Resistance R (I–P)*	Resistance RSI†	Comments
Radiant barrier	Metal film	4–12	0.7–2	Radiant barrier must face an air space R-value is a function of air space orientation and direction of heat flow Best for preventing heat gain through the roof
Vacuum	Panel	15–75	2.6–13	Because most heat flow is through the edges, larger panels are better Quality is most important to prevent loss of vacuum

*Resistance is $\frac{(ft^2)(°F)}{Btu/h}$ per inch of thickness except for the radiant barrier.

†Resistance is $\frac{(m^2)(°C)}{W}$ per meter of thickness except for the radiant barrier.

Table 15.6C I-P to SI Conversion Factors

Multiply	By	To Get
Resistance per inch (I-P)	6.933	Resistance per meter (RSI)
Actual resistance (I-P)	0.176	Actual resistance (RSI)
U-coefficient (I-P)	5.73	U-coefficient (SI)

miniature air spaces is vacuum insulation. All of these insulation types will now be described.

Batts and Blankets

Although most blankets or batts are made of fiberglass or rock wool, they are also made of cotton and cellulose. Blankets come in continuous rolls, while batts are precut to length. The batts and blankets are made to fit between studs, joists, or rafters. Both fiberglass and rock wool are very resistant to fire, moisture, and organic attack. The main health hazard is present during installation and comes from inhaling the short fibers that become airborne.

Loose Fill

Loose-fill materials consist primarily of fiberglass, cellulose (ground-up newspapers), and expanded minerals, such as perlite and vermiculite. The fiberglass and cellulose types are blown into stud spaces and attics. Cellulose is a good, safe product if properly treated with borates to make it fire-retardant and resistant to organic attack. Care must be taken to prevent inhalation of the fine particles both during installation and afterward. Perlite consists of lightweight granules that are usually poured into masonry wall cavities.

Foamed-in-Place

Most foamed-in-place insulation materials are made of plastics. The main exception is Air Krete, which is a foamed mineral that has the advantages of acting as a fire stop and of not releasing toxic gases. The plastic foams vary tremendously because of both the base materials and the foaming agents. Foams can be sprayed into cavities or on surfaces (e.g., basement walls) both during construction and for retrofit.

In all cases, the cured material needs to be covered to protect the foam and/or the occupants. Toxic smoke from burning plastic is a severe hazard, and off-gassing from aging plastic foams is a potential hazard, especially for chemically sensitive people. Because there are many differences among the plastic foams, see Table 15.6B for the specific characteristics of each type.

Boards

Although most insulation boards are made of foamed plastics, some are made from recycled or waste organic material. For example, Homosote is made from recycled newspapers. Boards can also be made of fiberglass and mineral wool. Because boards made of polystyrene are very resistant to moisture, they are frequently used to insulate below grade. Extruded polystyrene is both more resistant to moisture migration and has a higher R-value than the less expensive, expanded polystyrene (bead board) material.

Boards made of isocyanurate have very high R-values but are damaged by moisture and off-gassing. For that reason, they are sometimes covered with a protective foil coating. All plastic insulation boards should be covered to prevent damage to themselves from such forces as ultraviolet radiation in sunlight, water, and physical attack. They also need to be covered to minimize off-gassing and to prevent toxic smoke from being generated during a fire.

Air Spaces and Radiant Barriers

Large plain air spaces are a poor way to insulate. As Figure 15.6a shows,

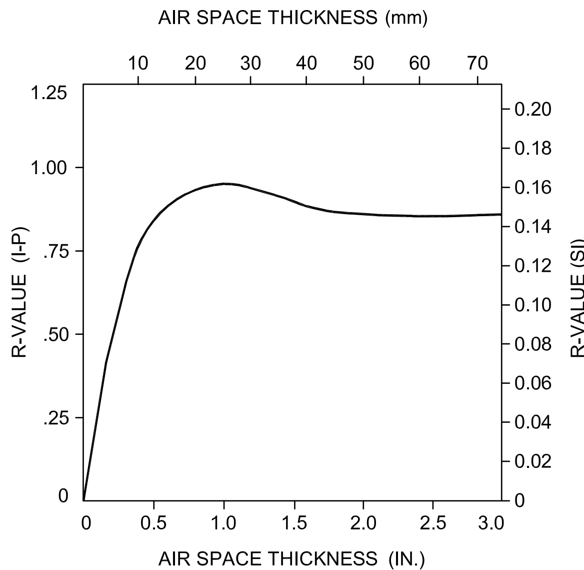


Figure 15.6b The optimum wall or window air space thickness is about ¾ in. (2 cm). Note that this graph is for air spaces not faced with reflective material. (After *Climatic Design*, by D. Watson and K. Labs, 1983.)

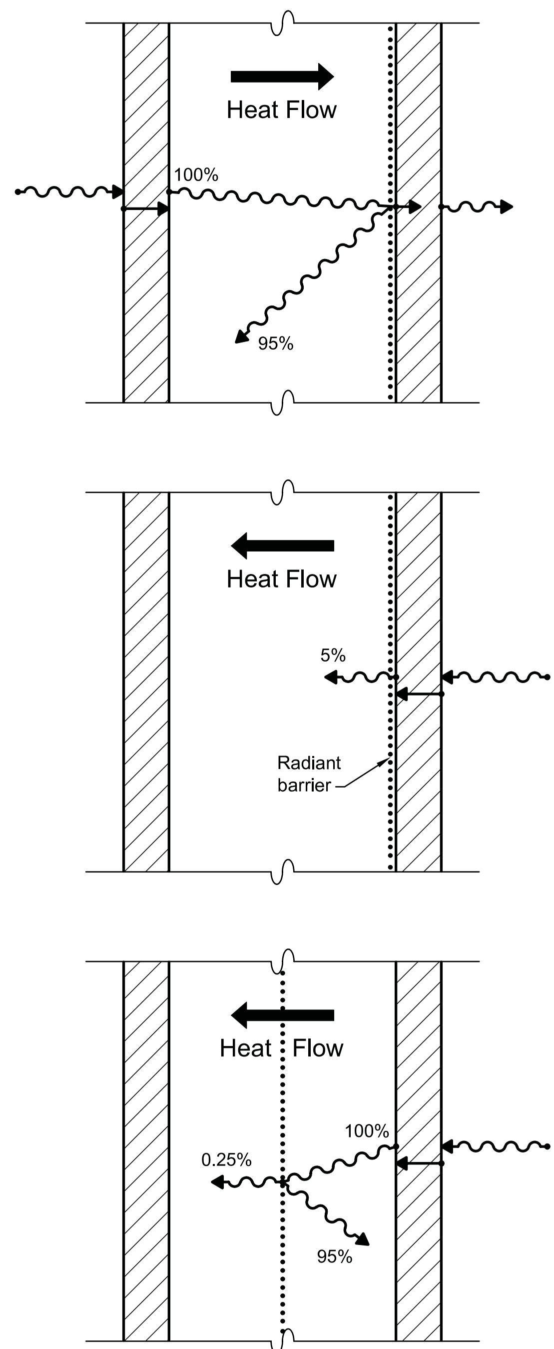


Figure 15.6c All radiant barriers act as either reflectors or nonemitters, depending on the direction of heat flow. A radiant barrier will reduce heat transfer either by reflecting 95 percent of the heat radiation or by emitting only 5 percent of that emitted by nonradiant barrier materials.

the R-value of an air space of any size is always less than 1 (0.16). The optimum size is about ¾ in. (2 cm) (Fig. 15.6b). For smaller air spaces conduction increases, and for larger ones, convection heat transfer increases. For more thermal resistance, air spaces should be filled with either insulation or a radiant barrier.

Although radiant barriers affect only the radiant transfer of heat, their effect can be quite significant. A radiant barrier consists of a highly polished metal foil that is both a poor emitter and a poor absorber (i.e., a good reflector) of heat radiation. Radiant barriers are usually made of aluminum, and they must face an air space at least ½ in. (12 mm) thick. They are usually applied to one or both of the materials facing the air spaces (Fig. 15.6c). A two-faced radiant barrier facing an air space on each side would reflect 95 percent and emit only 5 percent, so that it stops $(95 + 95(0.05)) = 99.75$ percent of the radiant transfer.

Additional layers of foil help little except to create additional air spaces, which reduce the convection heat flow. Although radiation is independent of orientation, heat flow by convection is very much dependent on both the orientation of the air space and the direction of heat flow. As a result, the resistance of air spaces with reflective insulation varies greatly with the location in the structure and the time of year. Table 15.6D gives the resistance of air spaces and reflective insulation for different orientations and heat-flow directions. Note the tremendous range of R-values for air spaces that are all about the same size but have radiant barriers.

The best application for a radiation barrier is in hot climates just under the roof. Experiments in

Florida have shown that the summer heat gain through the roof can be reduced as much as 40 percent with a radiant barrier. In buildings with rafters, the foil should be attached to the underside of the rafters to create two air spaces, each facing a radiant barrier. However, since working with the thin foil is difficult, most builders use foil pre-applied to the underside of sheathing panels.

In theory a radiant barrier on the floor of an attic will have the same effect as one attached to the underside of the roof, but the one on the floor will collect dust, making it useless.

Radiant barriers shine in hot climates under the roof facing the attic!

Table 15.6D R-Values of Air Spaces and Radiant Barriers*

	Air Space		Air Space with Radiant Barrier	
Position of Air Space	**R(I-P)**	**RSI**	**R(I-P)**	**RSI**
Wall	1	0.17	4	0.6
Ceiling in winter (heat flow up)	1	0.17	3	0.5
Ceiling in summer (heat flow down)	1	0.17	12	2.0

*Values vary somewhat with the size of the air space and with temperature.

Vacuum-Insulated Panels (VIPs)

To keep drinks hot or cold, a vacuum bottle is unbeatable. The vacuum stops all conduction and convection heat transfer, while a silver coating stops most radiant heat transfer (Fig. 15.6d). The bottle resists being crushed by the 1 ton/ft^2 (10,300 kg/m^2) atmospheric pressure only because of the sharp curvature of the glass, which acts as either a compression or a tension ring. Flat panels do not have that geometric advantage, and, therefore, need a spacer to keep from being crushed (Fig. 15.6e). Because the thermal resistance of the vacuum panel depends partly on the resistance of the spacer, the R-values of VIPs vary widely from R = 15 to R = 75 (RSI-2.6 to RSI-13).

Since the edges of the vacuum panels are heat bridges, larger panels have a higher total R-value. For example, a particular kind of VIP will have R-value of 40 if the area is 8 ft^2 and only R-20 if the area is 1 ft^2 because the edge losses have a larger impact (or in SI, a 0.8 m^2 panel has an RSI of 8, while a 0.1 m^2 panel only has an RSI of 4).

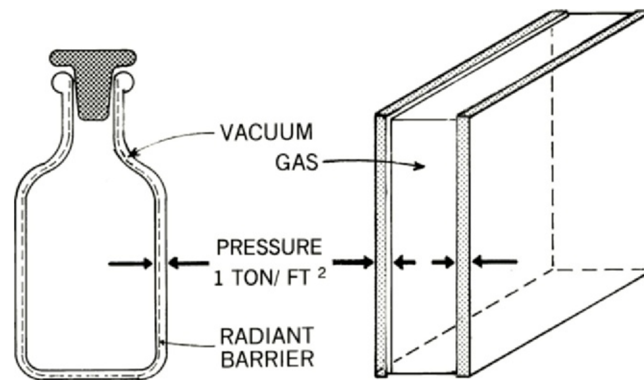


Figure 15.6d A vacuum bottle can stop most heat flow. It resists the 1 ton/ft^2 [100,000 pascals] atmospheric pressure by its sharp curvature, something a flat panel cannot do without a spacer.

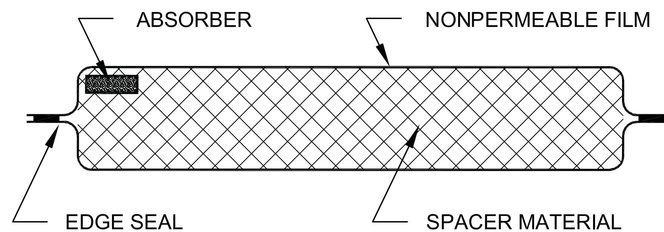


Figure 15.6e A vacuum-insulated panel (VIP) needs a spacer material such as fumed silica to resist atmospheric pressure. It also requires an absorber, which consists of a desiccant to absorb water vapor and a getter to absorb other gases to help preserve the vacuum. Although VIPs have great potential to save energy, their main weakness, as with windows, is edge losses. Thus, use the largest panels possible.

15.7 THE THERMAL ENVELOPE

The total thermal resistance of a wall, roof, or floor construction is simply the sum of the resistances of all the component parts. Determining the total resistance of a wall or roof section is useful for comparing alternatives, for complying with codes, and for calculating heat loss and heat gain. Many codes, company literature, and equations describe the thermal characteristic of a wall or roof by a quantity called the U-coefficient rather than the total R-value. The U-coefficient is the reciprocal of the total R-value (see again Chapter 3, Section 3.17). The author feels that the U-coefficient is a somewhat counterintuitive concept and that it is, therefore, usually better to think in terms of the total

R-value. (See Sidebox 15.7.) After all, it is easy to understand that a large total R-value is desirable, while it is harder to remember that a small U-coefficient is equally desirable.

Just as a container holding water should have no holes, a building holding heat in or out should have no thermal holes or thermal bridges. The thermal envelope should be a continuous unbroken skin around the conditioned spaces.

Walls

Although wall details vary tremendously, a few typical details are shown in Figure 15.7a. Note that most insulation materials should not be exposed either indoors or outdoors. Because the insulation between the studs is outflanked by the stud heat bridges, its effective R-value is only half of its rated value. Therefore, the R-value of the insulating sheathing is especially important and should be increased. Heat bridges will be discussed in more detail in the next section. The role of thermal mass will be discussed in Section 15.11.

Climate or Smart Facades

These types of facades have an additional glass skin, not to increase the thermal resistance but rather to allow for solar control and natural ventilation. Thus, they are not discussed here but in the chapters on shading and passive cooling.

Roofs

In flat-roofed buildings, the insulation should be on the top of the roof deck to avoid structural members, lighting fixtures, or air ducts penetrating the thermal envelope. In buildings with sloped roofs, the insulation should follow the rafters or the top chord of trusses. If the ridge is very high, the insulation can more efficiently follow the collar beams (Fig. 15.7b). These locations for the thermal envelope place the ductwork on the indoor side of

SIDEBOX 15.7

Total Resistance and U-Coefficient

The total resistance of a wall, roof, window, or door equals the sum of all the resistances of the components:

$$R_T = \Sigma R = R_1 + R_2 + R_3 \ldots$$

where

R_T = the total thermal resistance of the construction detail in R-value

$$R(I\text{-}P) = \frac{(ft^2) \times (°F)}{Btu/h} \quad \text{or} \quad R$$

$$R(S\text{-}I) = \frac{(m^2) \times (°C)}{W}$$

R_1, R_2, etc. = the thermal resistance of each component

Also, the heat-flow coefficient equals the reciprocal of the total resistance of a wall, roof, door, or window:

$$U = \frac{1}{R_T}$$

where

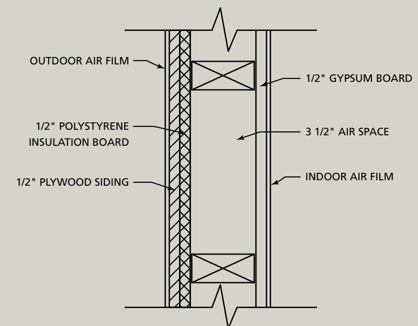
$$U(I\text{-}P) = \frac{Btu/h}{(ft^2) \times (°F)} \quad \text{or} \quad U(S\text{-}I) = \frac{W}{(m^2) \times (°C)}$$

U = the heat flow coefficient of the construction detail in U-value

Example*:* Find the total resistance and U-coefficient for the wood-framed wall detail below:

Component	*R-Values** R(I-P)	RSI
Indoor air film	0.7	0.12
½ in. (12 mm) gypsum board	0.45	0.08
3½ in. (87 mm) air space	1.0	0.17
½ in. (12 mm) extruded polystyrene board	2.5	0.43
½ in. (12 mm) plywood siding	0.6	0.11
Outdoor air film	0.2	0.03
Total resistance (R_T)	5.45	0.94
Total U-coefficient = $1/R_T$	0.18	1.06

*See Appendix J for an abbreviated list of R-values and U-coefficients. See the *ASHRAE Handbook of Fundamentals* for a complete list of values.



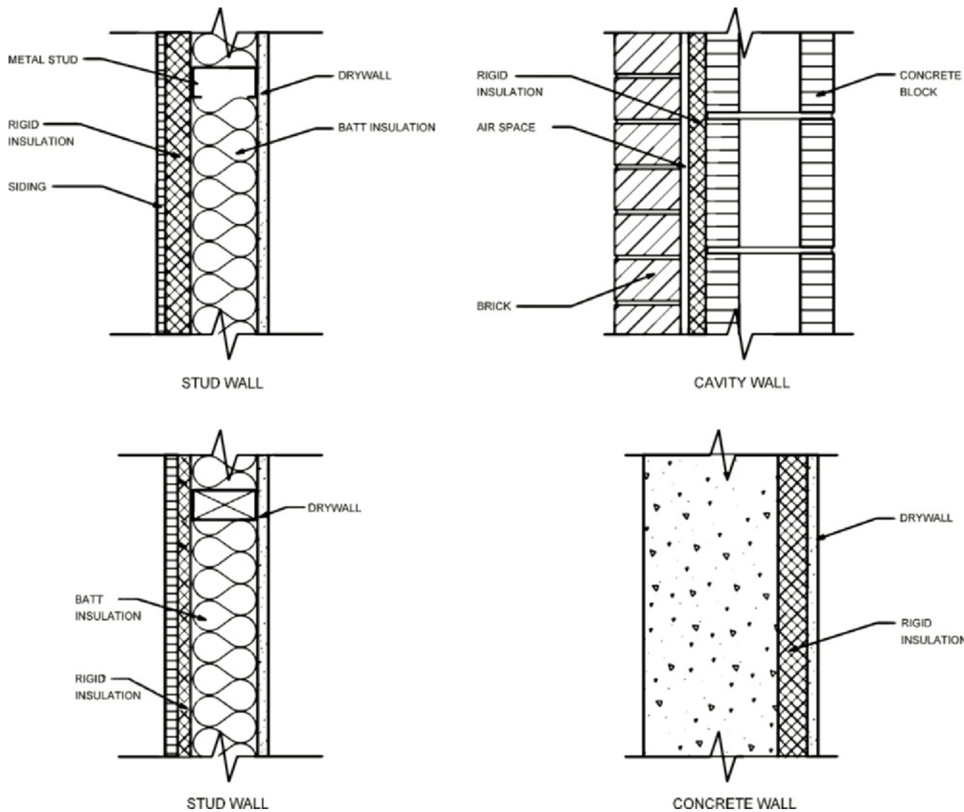


Figure 15.7a Details of various traditional wall types, showing the type and location of insulation. Note the extra-thick insulating sheathing as the primary thermal envelope component when using steel studs, since they are good heat bridges.

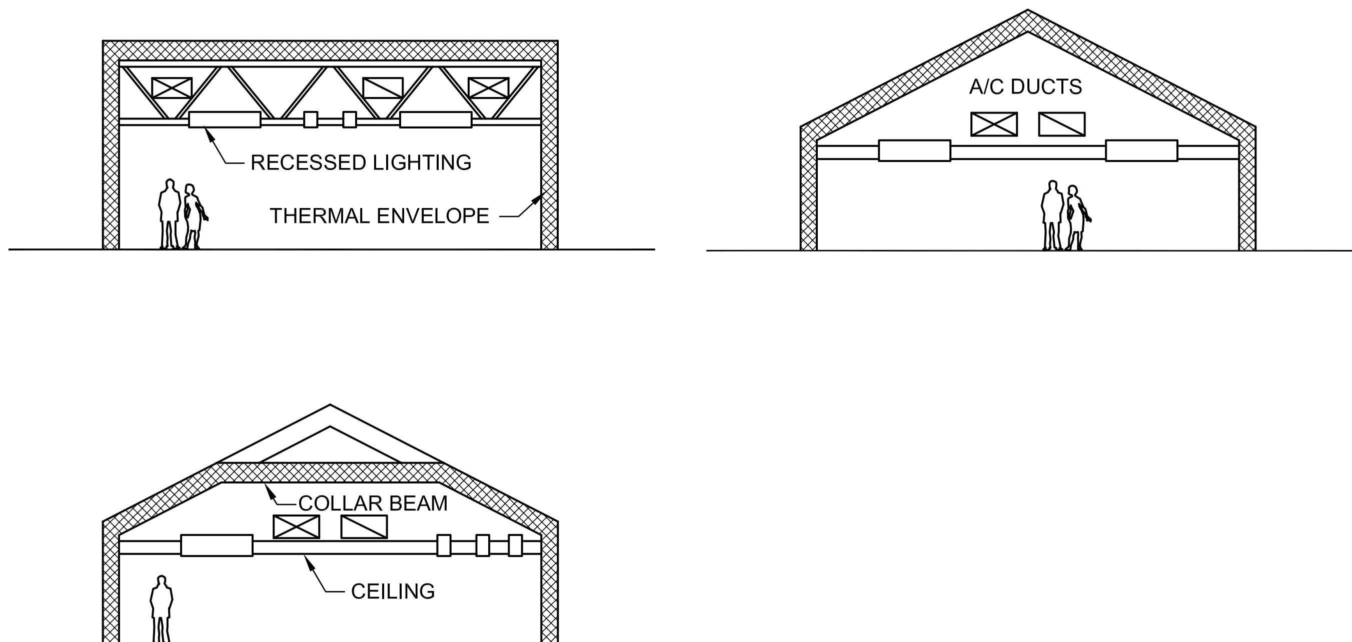


Figure 15.7b For flat-roofed buildings, the insulation should be on top of the roof deck so that all ducts, lights, and structural members are on the indoor side of the thermal envelope. Codes no longer allow placing insulation on top of hung ceilings. On sloped roofs, the insulation should follow the roof rafters and be placed between the rafters and/or on the roof deck. For steeply sloped roofs, the insulation can follow the collar beams, if they exist.

the thermal envelope, which is a very high priority.

Crawl Spaces

Although there are themal benefits to insulating crawl space walls and not venting the space, there are serious potential problems with the strategy: termites and health risks from radon, mold, and mildew. The safest strategy is to insulate the floor above the crawl space (Fig. 15.7c). Furthermore, ducts should never be placed in crawl spaces, as will be explained in Section 16.16.

Slab-on-Grade

Insulation is usually not required under a slab-on-grade except around the outside edge. Rigid insulation should extend down to the frost line

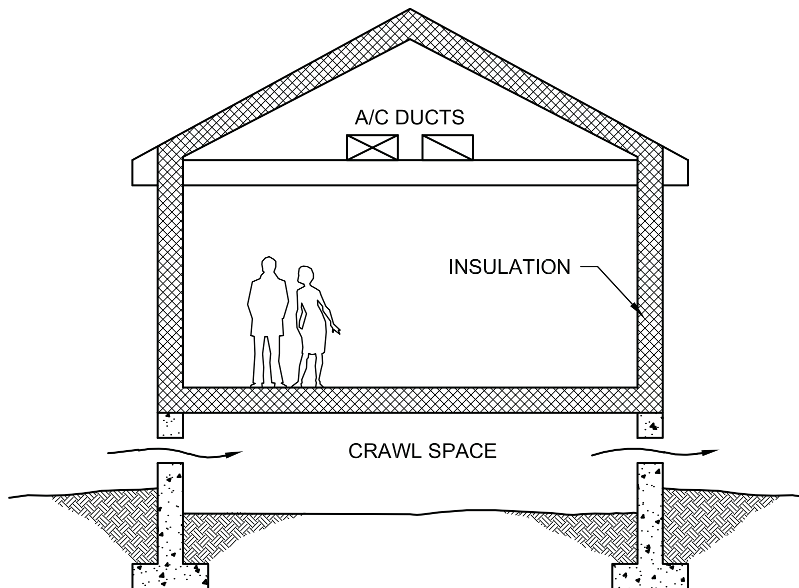


Figure 15.7c Crawl spaces are usually vented because of the problems of radon and moisture. Consequently, the floor above the crawl space must be well insulated.

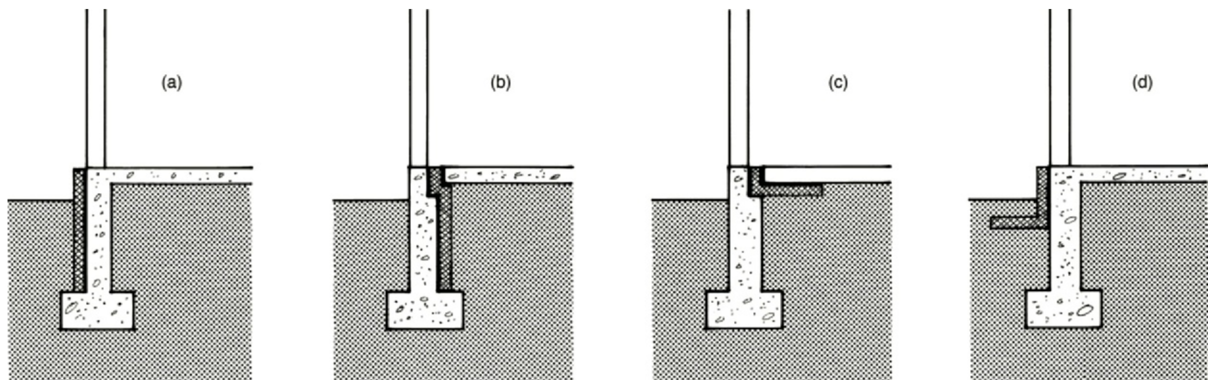


Figure 15.7d Alternative methods for insulating the perimeter of a slab. In all cases, the insulation forces heat to take a long (high-resistance) path through the earth. Methods (a) and (d) are preferred.

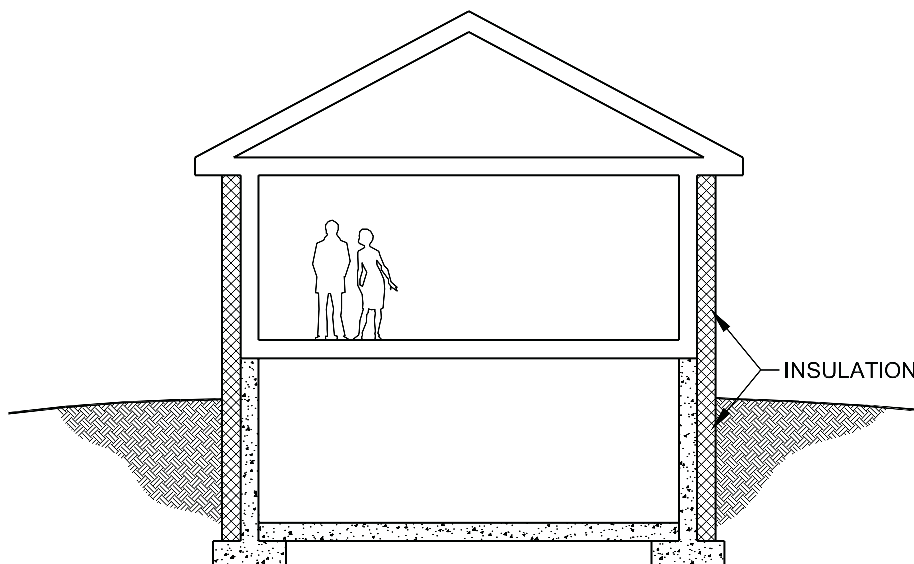


Figure 15.7e Insulate basement walls at least down to the footings.

or an equal distance sideways. Thus, the heat flowing through the earth is forced to take a very long and, therefore, high-resistance path (Fig. 15.7d).

Basements

Basements should be insulated on the earth side of the foundation wall all the way down to the footing (Fig. 15.7e). Since thermal mass is beneficial indoors, it is best not to insulate the foundation wall on the indoor side. Care must be taken to protect the foam insulation where it is aboveground. Polystyrene insulation, the usual choice, must be protected from ultraviolet radiation and physical attack with a protective finish such as stucco, special paints, sheet metal, cement boards, or treated wood. Although termites don't eat plastic insulation, they have no trouble making tunnels in it to reach wood.

Instead of adding insulation to a concrete wall, many insulating concrete form (ICF) systems are available that initially act as formwork and support for the steel reinforcing rods and then remain in place as insulation (Fig. 15.7f). The ICFs are either preformed blocks or panels with plastic ties. Most ICFs are made of polystyrene because that plastic is unaffected by water and, therefore, is safe belowground. The ICF systems are also used to build strong, energy-efficient walls above grade. However, the present design of ICFs insulates the thermal mass from the indoors as well as from the outdoors. A better ICF system would consist of more insulation on the outdoor side and a non-insulating panel on the indoor side.

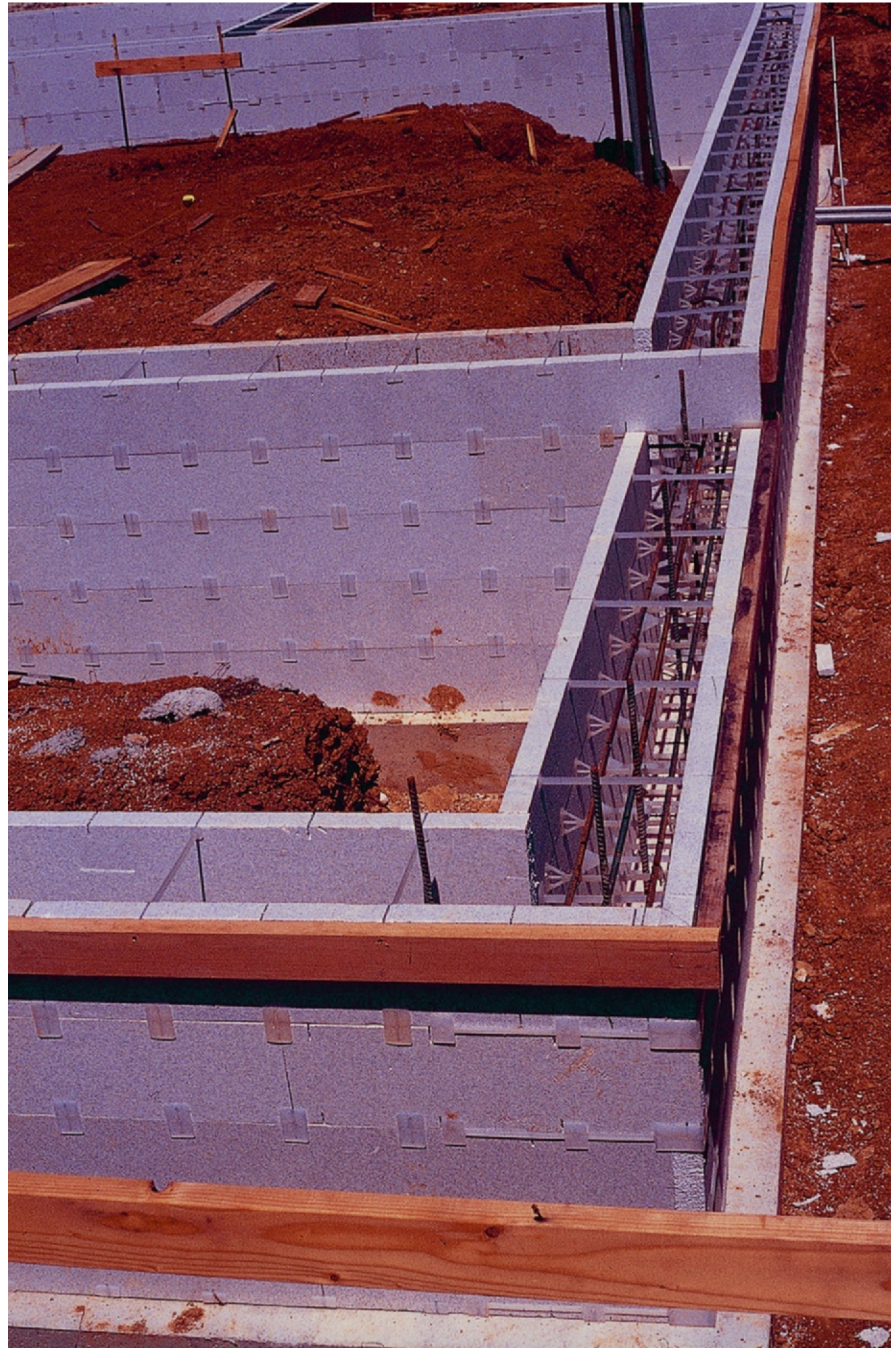


Figure 15.7f Insulating concrete forms (ICF) serve as both formwork and permanent insulation. Although mostly used for foundations, the forms are also used to build above-grade walls.

Structural Insulated Panels

Heat bridges are almost nonexistent with structural insulated panels (SIPs), which are sandwich panels fabricated in a factory, shipped efficiently (no boxes full of air), and erected in as little as one day (Fig. 15.7g). The panels connect with splice plates so that there are no studs to act as heat bridges (Fig. 15.7h). Thus, a 4 in. (10 cm) nominal SIP wall has an R-value of 14, while a similar framed wall has an actual R-value of about 10 (in RSI 2.4 rather than RSI 1.7). Furthermore, there is much less infiltration with the SIP than with standard construction.

Structurally, SIP panels are also superior to conventional framing. The facing boards, which can be made of a variety of materials, carry most of the load by the efficient stressed-skin mechanism. SIP systems also offer great design flexibility. The panels vary in thickness from 2 to 12 in. (5 to 30 cm) and can be as large as 8 × 24 ft (2.4 × 7.2 m).



Figure 15.7g Structural insulated panels (SIPs) create very high-quality thermal envelopes because of their high R-value and low infiltration. (Courtesy of Winter Panel, Brattleboro, VT.)

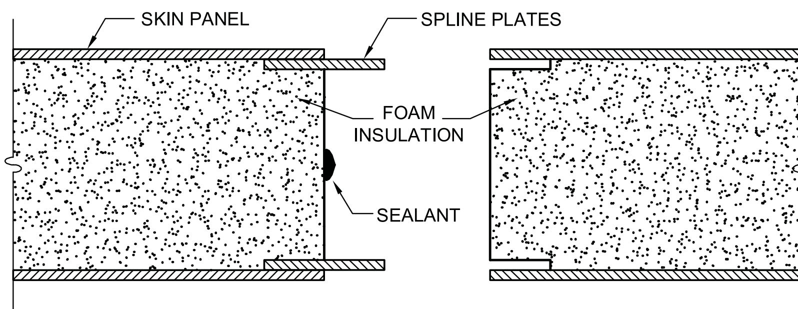


Figure 15.7h SIPs can eliminate studs by using splice plates that are glued and nailed into place. With sealant between panels, a very airtight building envelope is created. Skin panels can be made of OSB, drywall, or cement board.

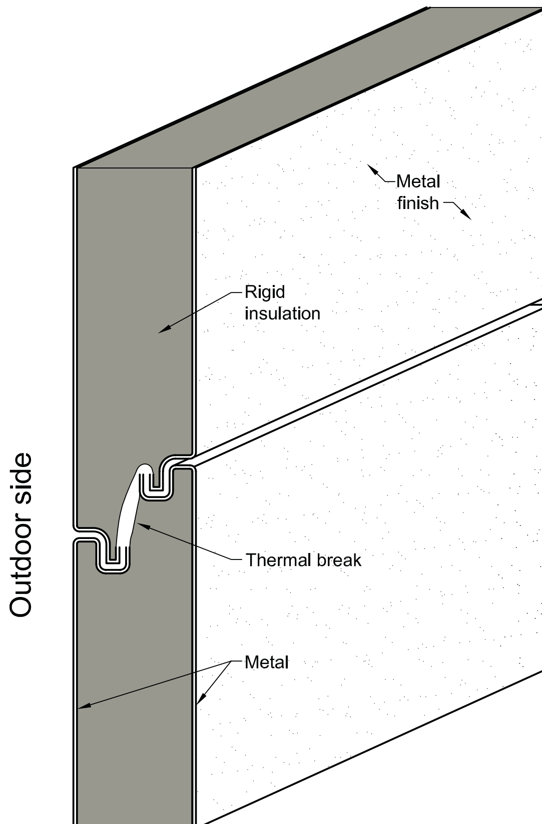


Figure 15.7i Insulated metal panels create continuous insulation because there is a thermal break at every panel edge.

Insulated Metal Panels

First used for walk-in freezers because of their great insulating value, insulated metal panels are now often used in building walls. Although similar to structural insulated panels, they do not support floor or roof loads, only wind loads. Even though their stressed skins are made of sheet metal, a large thermal break prevents heat bridges (Fig. 15.7i). At first, the metal insulated panels were the whole wall, with one metal skin being the outdoor finish and the other the indoor finish. Now they are also being used as high-performing sheathing panels, which allows for a very great variety of rainscreens (Fig. 15.7j).

Tilt-up Insulated Panels

In tilt-up construction, the concrete wall panels are cast directly on the floor slab to avoid the high cost of formwork. The panels are cast as a sandwich held together by special nonconducting connectors (Fig.

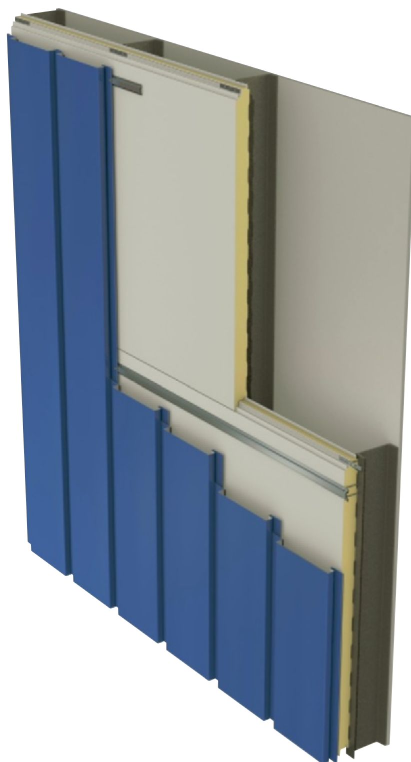


Figure 15.7j Insulated metal panels allow the hanging of fairly heavy rainscreens on the exterior face of the insulated panel without the need of direct connectors to the structure, which act as heat bridges. (© 2013 Metl-Span – A Division of NCI Group, Inc.)

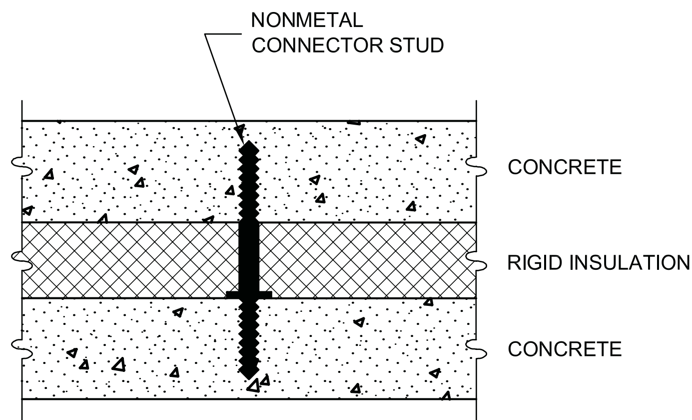


Figure 15.7k Insulated tilt-up panels use a low heat conducting tie to hold the two concrete panels together and to allow them to act as one structurally.

15.7k). Such tilt-up panels have many advantages: structural strength, insulating value, thermal mass, weather resistance, and fire resistance.

Straw Bales

Although straw bales are not as insulating as many advocates claim, the total R-value of a straw bale wall is excellent because the walls are so thick. Research at the Oak Ridge National Laboratory in Tennessee has shown straw bales to have an R-value of about 1.4 per in. (in SI 10 per m). Their main virtue is that they are recycled natural materials. When covered with cement stucco, they become a safe and healthy building system. The bales should be used as an infill and not as structural material (Fig. 15.7l).



Figure 15.7l Straw bales are generally used as infill panels, rather than being load-bearing.

Adobe and Rammed Earth

Because traditional adobe or sun-dried mud brick construction uses no insulation, it is appropriate only for hot and dry climates with no winters (Fig. 15.7m). Insulation is a must



Figure 15.7m Adobe, or sun-dried mud bricks, are being made in this Mayan village in Guatemala. The best adobe bricks are made of a clay-straw mixture. The straw gives the dried brick some strength in tension.

whenever there is a need for heating or air-conditioning.

Instead of making bricks, the mud can be placed in forms similar to the ones used for concrete. The mud is then compacted with power equipment, if available. When the forms are removed, the rammed earth walls are similar to those built of adobe. Because both systems have little resistance to earthquakes, they should be used only as infill in seismic regions. Unfortunately, rammed earth walls and adobe are hard to insulate.

15.8 HEAT BRIDGES

The actual heat gain and heat loss of a building are usually much greater than what the design of the thermal envelope would predict. Traditionally, infiltration was the main cause of poor performance, but tighter construction and "house wraps" have reduced infiltration significantly. Now the main problem is often a result of heat bridges and holes in the thermal envelope (Fig. 15.8a).

In framed construction, the wood studs, plates, and other framing members are heat bridges, reducing the performance of the insulation by about 20 percent. If steel studs are used, the insulation's effectiveness is reduced at least 50 percent (Tables 15.8A and 15.8B). Note that SIP panaels lose only about 7 percent of their R-value due to heat bridges. See Table 15.8B for a more detailed analysis of steel studs. For example, in a wall of 2 × 4 steel studs, 16 inches on center, the R-15 batt insulation will perform as if it were only R-6.4, or 43 percent as good. In other words, you pay for R-15, but you only get the benefits of R-6.4.

Consequently, insulation should be on the exterior of steel framing members and not between them. Energy codes now require continuous insulation to minimize the problem of heat bridges (Fig. 15.8b). With steel studs, it is best to leave the cavities free for mechanical and electrical equipment. Although the problem of heat bridges is less severe with wood framing, continuous insulation should nevertheless be used in addition to cavity insulation. Another method for reducing bridging from wood studs is to use larger studs at greater spacing (Fig. 15.8c).

Common heat bridges also result from the use of structural sheathing at corners to brace the building. Instead, use let-in diagonal bracing as shown in Figure 15.8d. When trusses are used and the insulation is placed along the bottom chords, the web members all penetrate the insulation. When the trusses are made of steel, major heat bridges are created (Fig. 15.8e).

Curtain wall systems without thermal breaks have major heat bridges. Quality curtain wall systems will have plastic spacers to create thermal breaks between the outdoor and indoor facing metal parts (Fig. 15.8f). Metal window



Figure 15.8a The saying "out of sight, out of mind" is usually appropriate for heat bridges, but not in this case. The significant heat bridges from the structure and roof fasteners are glaringly obvious in this photo of a snow-covered flat roof. (Courtesy of Thomas Kelly and the 2001 Company.)

Table 15.8A Thermal Bridging's Effect on Insulation

Framing System	De-rating Factor*
2 x 4 wood	80
2 x 4 steel	50
SIP	93

*A de-rating factor of 100 percent indicates that there are no heat bridges.

Table 15.8B ASHRAE Correction Factors for Metal Framing

Stud Size	Stud Spacing	Cavity Insulation	Correction Factor	Effective R-value
2 x 4	16″ o.c.	R-11	0.50	R-5.5
		R-15	0.43	R-6.4
2 x 8	16″ o.c.	R-25	0.31	R-7.8
	24″ o.c.	R-25	0.38	R-9.6

Notes:
1.This is only part of a larger table from the American Society of Heating, Refrigeration, and Air Conditioning Engineers (ASHRAE).
2.The cavity insulation R-value is what is specified and purchased.

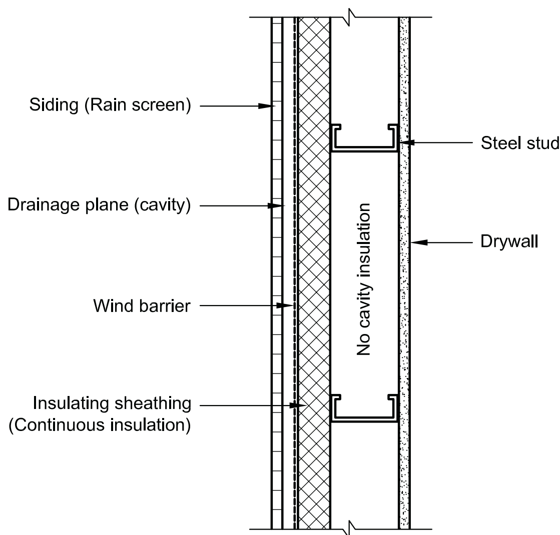


Figure 15.8b When steel studs are used, all of the insulation should be concentrated in the sheathing, because the cavity insulation is less than 50 percent effective.

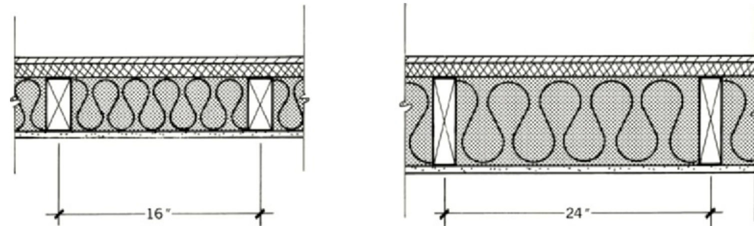


Figure 15.8c Heat bridges caused by studs are greatly reduced by using 2 × 6 studs every 24 in. instead of 2 × 4 studs every 16 in. on center.



Figure 15.8e Serious heat bridges are created in this attic by the web members of steel trusses when the insulation is along the bottom chords. Not only is heat conducted efficiently through the insulation, but it is also transferred efficiently to or from the bottom chords of the truss, which are in contact with the interior of the building.

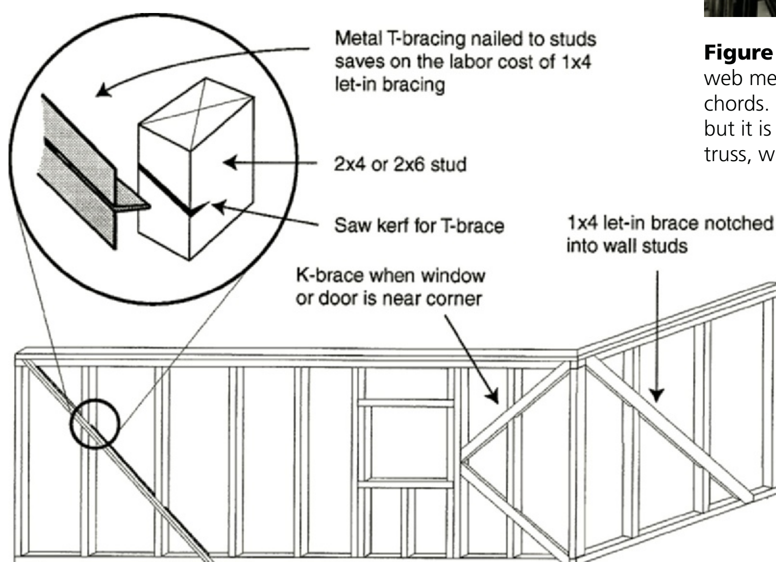


Figure 15.8d Let-in bracing using either wood or steel diagonal members allows for the uninterrupted use of continuous insulation. (of Southface Energy Institute.)

frames also create large heat bridges that can be reduced either with thermal breaks or by substituting wood, vinyl, or fiberglass for the frames.

Poorly installed insulation is also a significant problem because small air spaces act as thermal holes. For example, attic insulation with 5 percent voids can reduce the overall R-value by over 30 percent. Voids in insulation are quite common because of obstacles like electrical wires, pipes, framing members, and poor craftsmanship.

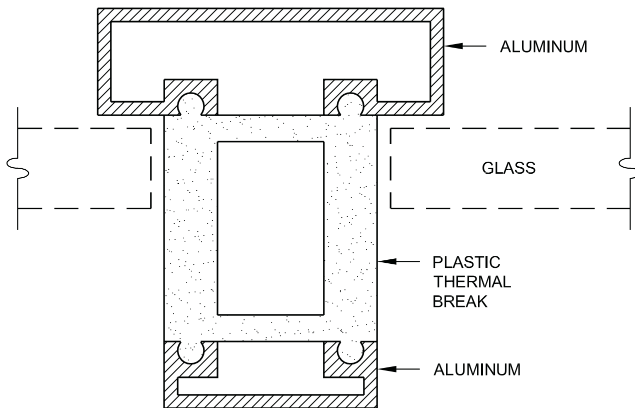


Figure 15.8f Curtain wall systems should have thermal breaks to prevent heat bridges. A detail of a schematic mullion is shown.

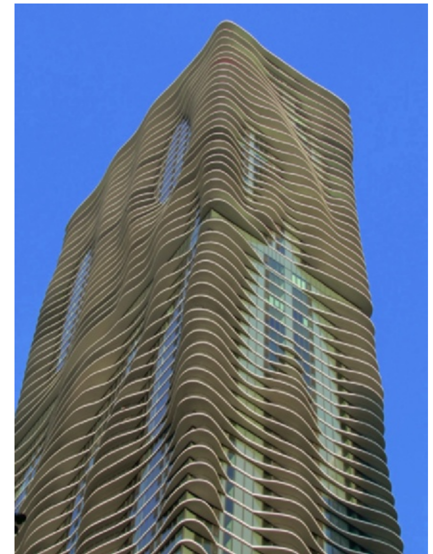


Figure 15.8h Concrete balconies that cantilever from concrete floor slabs are major heat bridges. They turn a building into a giant radiator both summer and winter. Ironically, the Aqua Tower building was promoted as a model of sustainability.



Figure 15.8g Exposing floor slabs for aesthetic expression is unsustainable because of the large heat bridges created.

A fairly common aesthetic idea is to express each story by exposing the slab edge. Unfortunately, that creates major heat bridges and makes the buildings unsustainable (Fig. 15.8g). Even worse are cantilevered concrete balconies, so common and so unnecessary, especially in cold climates like Toronto and Chicago (Fig. 15.8h). Exposed slab edges and cantilevered concrete balconies are such huge heat bridges because heat flows in three dimensions. A thermogram shows them for what they are: buildings with cooling fins in the



Figure 15.8i Instead of being cantilevered, balconies can be supported by diagonal ties, brackets, or columns.



Figure 15.8j Here, a structural thermal break is used to separate the cantilevered concrete balcony from the floor slab. (Courtesy of Schöck USA. Inc.)

winter and heating fins in the summer (Colorplate 2). Instead of cantilevers, balconies can be hung from the building or supported by columns. Balconies, however, can be cantilevered without creating major thermal bridges if they use structural thermal breaks, as shown in Figure 15.8j.

A building with significant defects in its thermal envelope, as clearly demonstrated by the thermograms of Colorplates 2, 5, and 6, should be just as unacceptable as a building that lets the rain enter. Sustainability requires energy to be used efficiently and not wasted. Fortunately, building codes and the design community are rapidly realizing the seriousness of heat bridges and holes in the thermal envelope, and they are finding creative ways to eliminate them.

15.9 WINDOWS

Windows account for about 30 percent of the heating and cooling load of a building, and they have a large impact on thermal comfort because of their effect on the mean radiant temperature (MRT).

The bar chart of Figure 15.9a shows the comparative thermal resistance of different window systems. Note that although double glazing is about twice as good as single glazing in stopping heat flow, it is still only about one-ninth as effective as an ordinary insulated stud wall.

Even with a low-e coating, a double-glazed window has an R-value of 3, which is still only one-sixth as good as a standard wall. Nevertheless, on south windows, that results in a heat gain during the whole winter, because the passive solar heating during the day exceeds the heat loss at night.

The old wisdom, to minimize windows in cold climates, has changed if high-performance windows are specified, especially on the south (Fig. 15.9b).

Consider the strange fact that switching from R-2 windows to R-4 windows can have the same benefit as switching the walls from R-19 to R-100. This unbelievable situation is correct because south, east, and west windows not only lose heat but also collect heat from sunlight. Thus, an opaque wall would have to have an R-value of 100 (17 SI) to have the same net heat loss as some windows with an R-value of 4 (0.7 SI). It is important to note that this relationship between the benefits of window R-value and equivalent wall R-value is very orientation-dependent and somewhat climate and latitude-dependent as well. Almost everywhere, however, south windows collect more heat than they lose in the winter. Thus, they perform better than a wall with an infinite amount of insulation, while high R-value east and west windows can perform about the same as super-insulated walls. Consequently, windows do not need to have the same R-value as walls in order to avoid being holes in the thermal envelope in the winter, and in the summer, shading is more important than thermal resistance.

The glazing itself, whether glass or plastic, has almost no thermal resistance. It is mainly the air spaces, the surface air films, and low-e coatings that resist the flow of heat (Fig. 15.9c). Single glazing has no air spaces, but it does have the slightly insulating stagnant air films that exist whenever air comes in contact with a building surface. The air spaces can be filled with dry air, but the resistance of the air space can be significantly increased by replacing the air with argon, krypton, or xenon. The R-value improvements are: argon +½, krypton +1; and xenon +1.

The thermal resistance of a window consists of two parts: the glazing and the frame. In large windows, most of the heat is lost through the glazing, but in smaller windows, the frame becomes critical. Most frames are made of wood, vinyl, fiberglass, or aluminum. Wood has good thermal properties, and when it is protected with vinyl or aluminum, it becomes a durable, low-maintenance

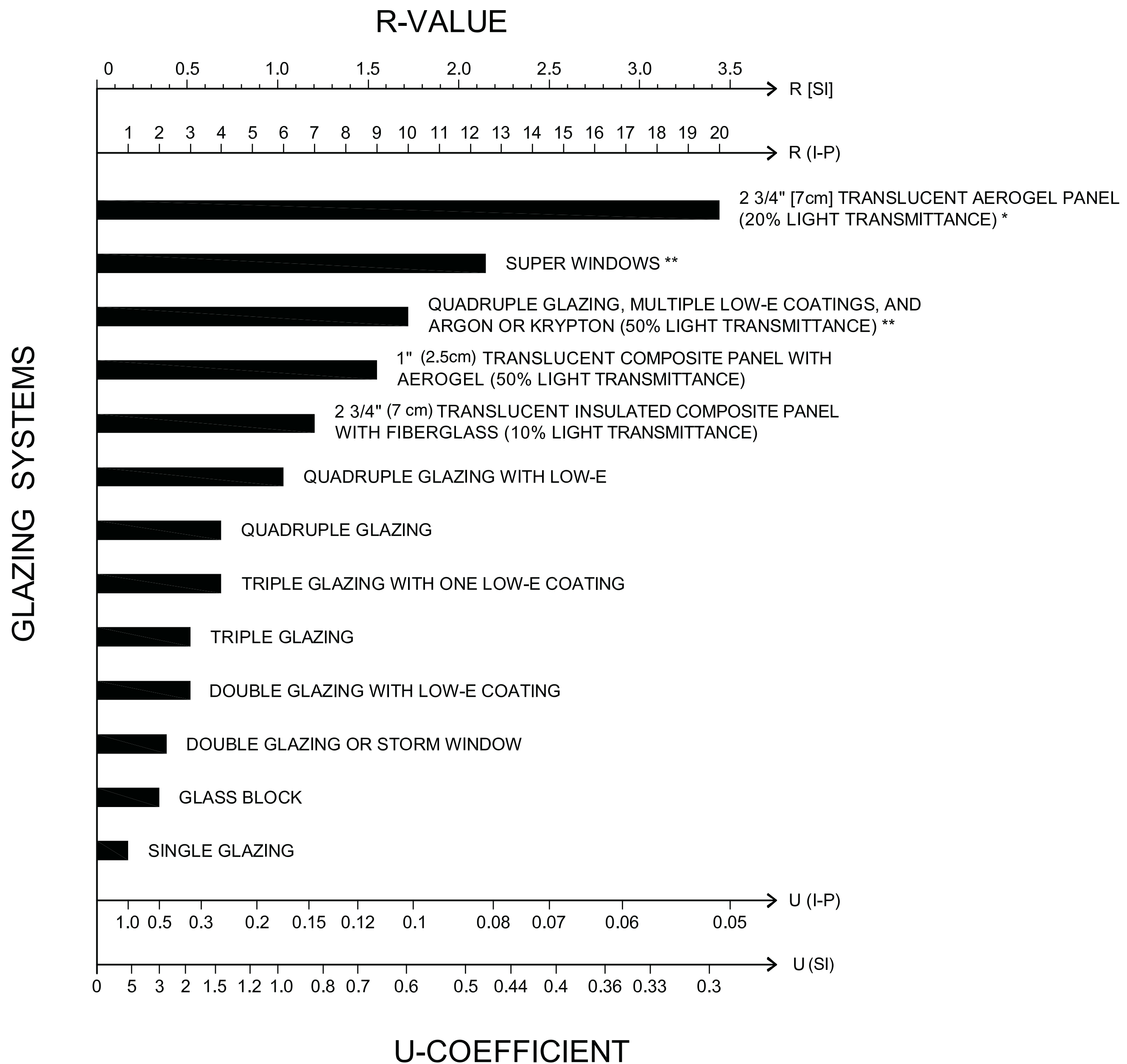


Figure 15.9a The thermal resistance and U-coefficient of various window systems are shown. The values shown are for total resistance, which includes the resistance of the air films, air spaces, low-e coatings, and any special fill gases. Actual R-values vary somewhat with temperature, type of glazing, type of coating, thickness of air space, and the effect of the frame. Most plastics are similar to glass when used as glazing. Note that the RSI scale in this chart is for the actual RSI-value and not for a meter thickness as in Figure 15.6a.

product. Vinyl and fiberglass also have low conductance, while metal is acceptable only if it has thermal breaks.

In double or triple glazing, heat is also lost through the edge spacers (Fig 15.9d). High-performance windows use edge spacers with thermal breaks. The edge spacers not only maintain the size of the air space, but also keep dirt and moisture out in order to prevent condensation (fogging) inside the window.

The air films and air spaces control only the heat flow by conduction and convection. To reduce heat flow further, radiation must also be considered. Although clear glass is mostly transparent to solar radiation, it is opaque to heat radiation. Since most of this long-wave infrared (heat) radiation is absorbed, the glass





Figure 15.9b Which building will require less heating energy? Until the 1980s, the building on the left would have had less heat loss, but with new, high-performance windows, the building on the right has the lower heating bills, especially if most windows face south. (Courtesy of Anderson Corp., Bayport, MN)

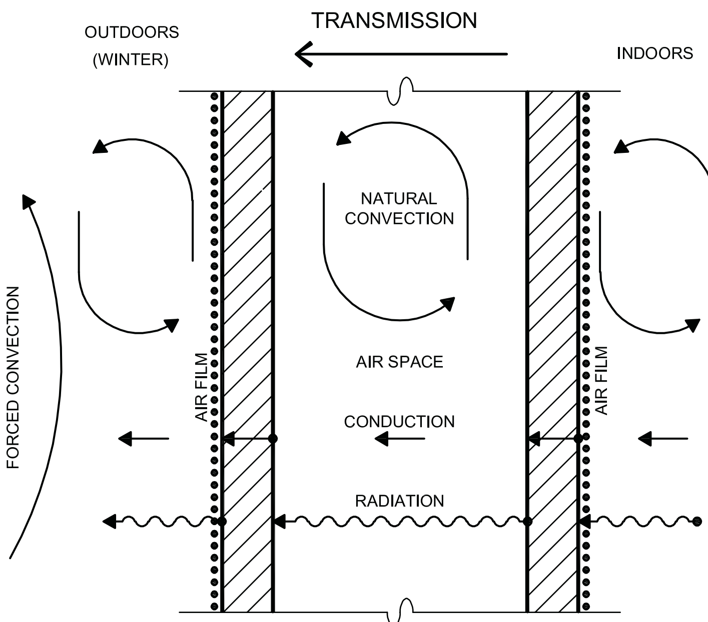


Figure 15.9c Since glass is a good conductor of heat, most of the resistance to heat flow comes from air films and air spaces (if any) and coatings (if any).

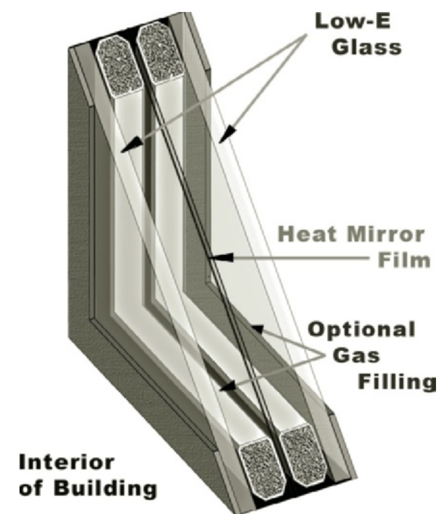


Figure 15.9d This cutaway drawing shows a special kind of triple-glazed window that uses a plastic film instead of the central glass pane to create a lighter and less expensive window. The center-of-glass thermal resistance varies with the fill gas used (argon, krypton, or xenon) and the number of low-e coatings. R-values range from 4 to 9 (0.7 to 1.6 SI). Efforts are also being made to reduce the heat bridges of the edge spacers. (Heat Mirror is a registered trademark of Southwall Technologies, Inc.)

gets warmer, and, consequently, more heat is given off from both indoor and outdoor surfaces (Fig. 15.9e). Thus, in effect, a significant amount of the radiant heat is lost through the glazing. Special coatings on the glass can dramatically reduce this radiant heat loss.

Various types of reflective coatings are possible. A transparent silver coating (any polished metal) will not only reflect much of the long-wave heat radiation, but also much of the solar radiation (visible and short-wave infrared) (see Fig. 15.9f). Because it reflects heat radiation in the summer, it has a higher R-value than clear glazing. This kind of coating is appropriate for buildings that need year-round protection from the sun. However, if winter solar heating and/or daylighting is desirable, a different kind of coating will be required.

Special coatings called **low-e** (low-emissivity) are available that transmit solar radiation but reflect long-wave infrared radiation. One type of low-e coating is for those buildings that need to reduce winter heat loss and at the same time allow the sun to shine in (i.e., passive solar) (Fig. 15.9g). Because the low-e windows reduce heat flow, they are given a higher R-value. The bar graph in Figure 15.9a shows how each low-e coating is about equivalent to an

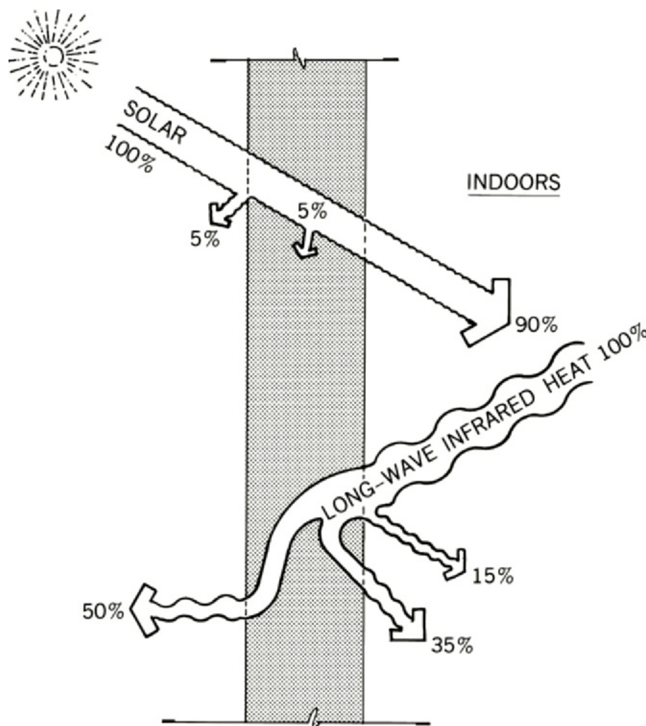


Figure 15.9e Although clear glass transmits most solar radiation, it absorbs most of the long-wave infrared (heat) radiation. Much of this absorbed heat is then lost outdoors. In the summer, the flow of heat radiation is from the outside in.

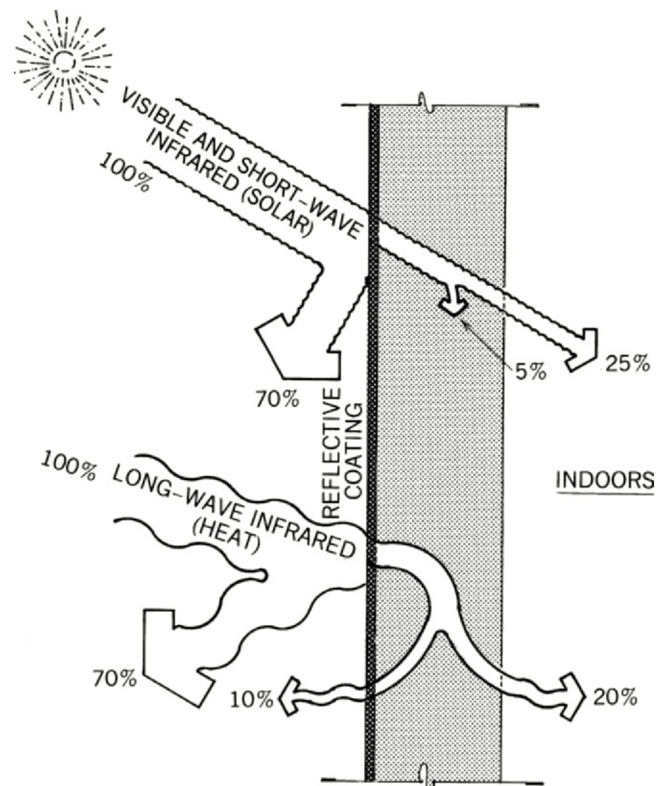


Figure 15.9f A metallic coating on glass reflects most of the solar and heat radiation. Although good in summer, heat gain is also reduced in the winter, and daylighting is lost all year.

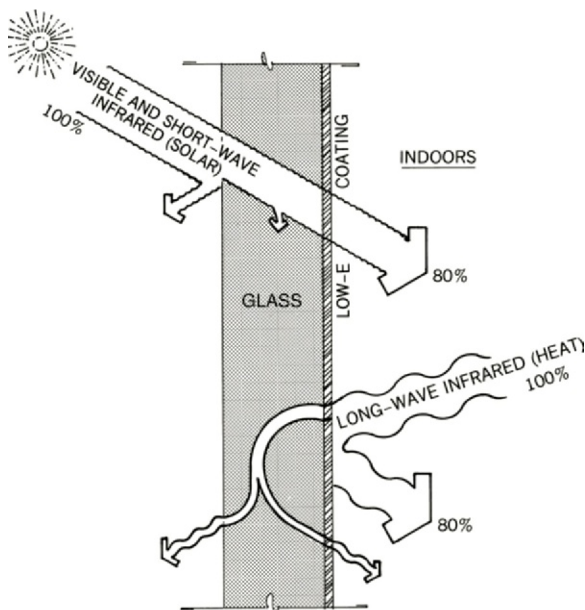


Figure 15.9g Low-e coatings are good for colder climates because they allow high transmission of solar radiation while they reflect heat radiation back indoors.

additional pane of glass (and air space) in R-value but without the equivalent increase in the weight or cost of the glass. The cost of double-glazed low-e windows is low enough that it should be the minimum standard, except in the mildest climates. The benefits are many: significant energy savings, increased thermal comfort, reduced condensation (fogging), and reduced fading from ultraviolet radiation.

A slightly different low-e coating was described in Figure 13.7. In those cases where the light but not the heat of the sun is desired, a selective low-e coating is used. This type of coating is transparent to visible radiation but reflective to both short- and long-wave infrared radiation. This kind of coating is appropriate for daylit internally dominated buildings, such as large office buildings, in all but very cold climates (Fig. 15.9h).

Because there are now many different kinds of low-e coatings available, glazing should be specified by both its R-value and its solar heat gain coefficient (SHGC). Thus, the glazing specified would vary with building type and climate. It would also be "tuned" in that it would vary with orientation in any one building.

In general, the higher the R-value of glazing (i.e., the more layers of glass) the lower the solar transmission, which is unfortunate because in

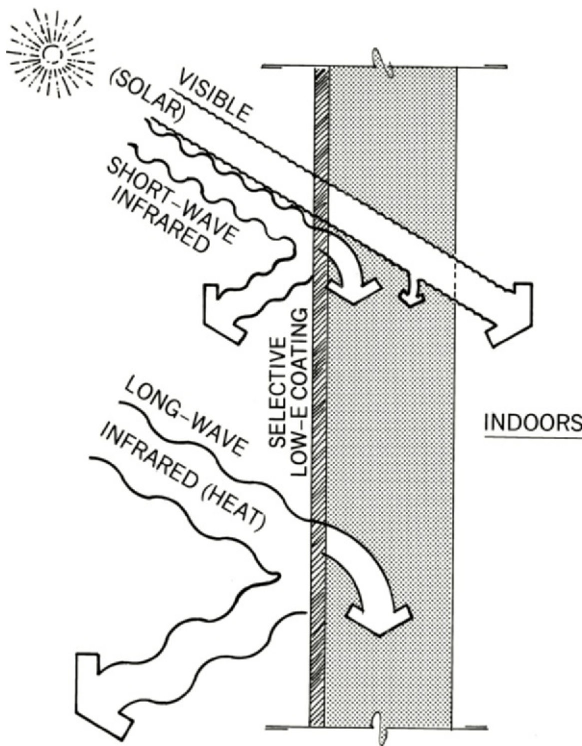
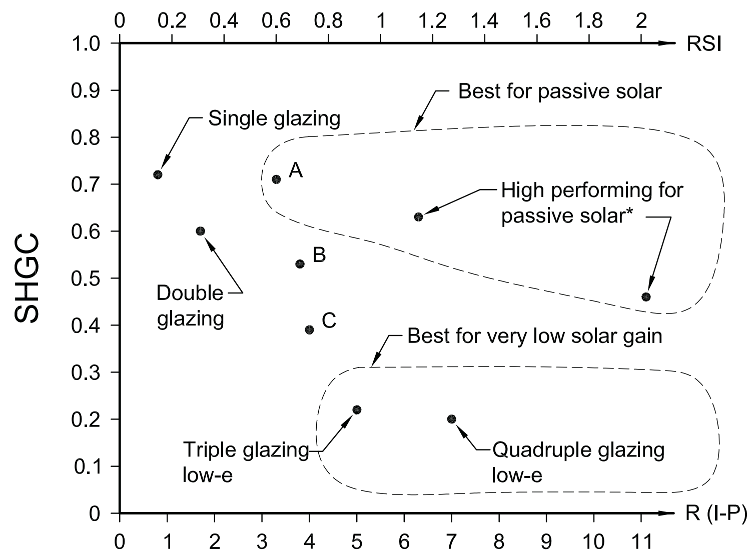


Figure 15.9h When light but not heat is desired, a spectrally selective low-e coating should be used.



	Glazing	Type of low-e	SHGC	R_T
A	Double	For high solar gain	0.71	3.3
B	Double	For moderate solar gain	0.53	3.8
C	Double	For low solar gain	0.39	4.0

* Alpen windows (TM)

Figure 15.9i The upper right part of the graph represents conditions ideal for south glazing in cold climates (i.e., both very good R-value and solar heat gain). The bottom right part of the graph represents ideal conditions for east and west windows in climates that are hot in the summer and cold in the winter (i.e., high R-value and low solar heat gain). Points A, B, and C represent double glazing with three different types of low-e coatings.

cold climates both high R-value and high solar gain are desired on south windows. However, the graph in Figure 15.9i shows that manufacturers have developed glazing that gives a good combination of R-value and solar gain.

Do not select and specify a window unless you know both its R-value (U-coefficient) and its solar heat gain coefficient (SHGC)!

The National Fenestration Rating Council (NFRC), a nonprofit corporation, evaluates and labels windows of many companies. Such ratings promote quality, and NFRC ratings are increasingly being used by energy codes to maintain the minimum quality of construction.

As mentioned before, a dynamic environment requires a dynamic response. During the day, windows are an asset, providing views, daylight, and solar heating; but at night, windows are a liability, because they lose light and, in the winter, they also lose heat. Movable insulation can respond to the dynamic needs of windows.

Building glazing should be tuned! Use different glazing systems on the south, north, and east/west facades!

15.10 MOVABLE INSULATION

Movable insulation can greatly improve the performance of windows. The benefits of movable insulation are many: extra insulation on winter nights, higher mean radiant temperature at night, reflection of indoor light (elimination of the black hole effect of windows at night), extra insulation and shading during summer days whenever view and daylight are not needed (e.g., when no one is in the building), and aesthetic value.

Because windows are now available with R-values as high as 10 (RSI-1.7), it might seem that movable window insulation is no longer necessary. However, high R-value windows are expensive, don't reflect light back inside at night (black hole effect), don't shade as well during a summer day, and block too much winter sun on south windows. Consequently, movable window insulation is still practical, especially on south windows.

Movable insulation for windows comes in many forms. Although outdoor shutters also provide extra security, they have limited thermal benefits because the wind tends to short-circuit any thermal performance of the shutters (Fig. 15.10a).

Seals are less important indoors, but short-circuiting convection must still be prevented (Fig. 15.10b left).

Drapes with thermal liners are very appropriate since curtains of some kind are often specified anyway for aesthetic and lighting reasons. With an insulating foam or reflective films, drapes or shades can increase the R-value of a window as much as three R-units. Care must be taken, however, to prevent the short-circuiting of the insulation by sealing the edges (Fig. 15.10b). Top and bottom seals are best accomplished by having the drapes extend from the ceiling to the windowsill or floor, while magnetic strips or Velcro can be used to achieve good edge seals. The drapery should also contain a vapor barrier to reduce condensation on the windows. One company called "WindowQuilt" makes a roll down insulation system that has an R-value of 4.6 and blocks most solar gain in the summer.

Venetian blinds with a reflective coating (i.e., radiant barrier) can effectively control daylight, heat gain, and to some extent heat loss (Fig. 15.10c). Readily available are cellular shades that open like an accordion (Fig. 15.10d). When the inside of the cells are covered with a radiant barrier and the edges have side seals, they have an R-value of about 4 (RSI-0.3), which is very good for a window covering.

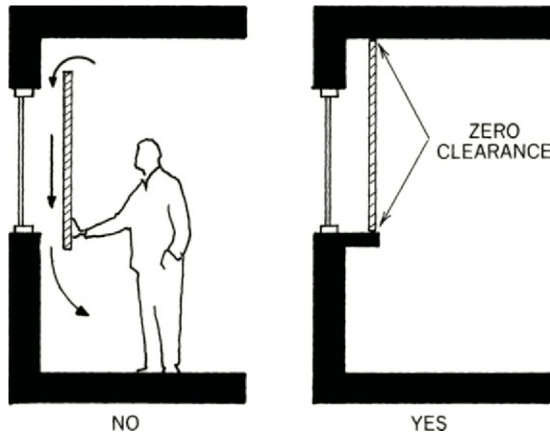


Figure 15.10b Prevent natural convection air currents from short-circuiting movable insulation, such as thermal drapery, by sealing the edges.

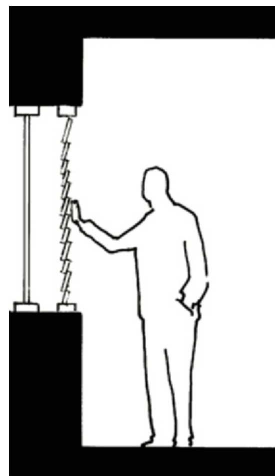


Figure 15.10c Venetian blinds with a reflective coating can improve the R-value of the windows when they are rotated into the closed position during winter nights and summer daytimes.

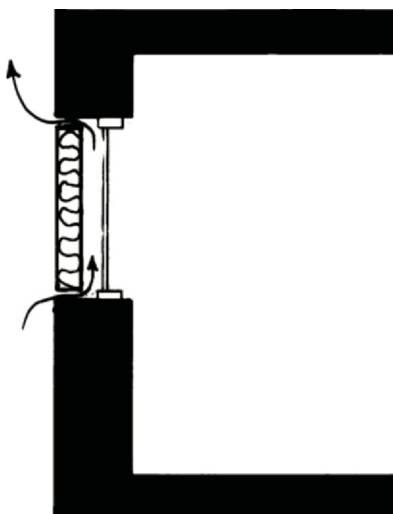


Figure 15.10a Outdoor shutters are rarely effective insulators because the wind will get behind the seals.

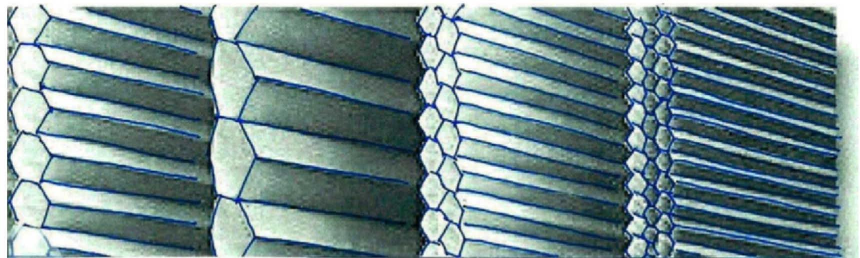


Figure 15.10d Cellular window shades are available with either one, two, or three insulating air spaces. Their performance is greatly improved by having the inside of the cells covered with a radiant barrier. They perform even better when provided with side seals.

15.11 INSULATING EFFECT FROM THERMAL MASS

Thermal mass has many benefits. It stores heat for passive solar, can be used as a heat sink for night-flush cooling, can reduce peak electrical demands due to air-conditioning, and can reduce heat gain through a wall. Since thermal mass is usually expensive and since it has a high embodied energy content (especially if it is concrete), it should be used to provide as many benefits as possible. In previous chapters, we have discussed the role of thermal mass

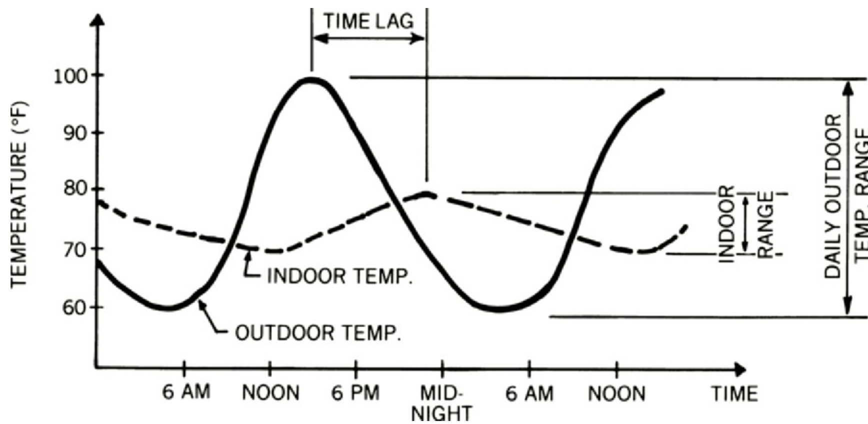


Figure 15.11a The difference between the times when the outdoor and indoor temperatures reach their peaks is called the time lag, and massive walls generate much more time lag than lightweight walls.



Figure 15.11b Because adobe (sun-dried mud bricks) is a structurally weak material, the walls must be very thick, which increases adobe's thermal benefits in hot and dry climates. Since mud is an inexpensive material, adobe was popular when labor was also cheap, as seen in this historic New Mexico church.

Table 15.11 Time Lag for 1 ft (30 cm) Thick Walls of Common Building Materials

Material	Time Lag (hours)
Adobe	10
Brick (common)	10
Brick (face)	6
Concrete (heavyweight)	8
Wood	20*

*Wood has such a long time lag because of its moisture content and high thermal resistance.

for passive solar heating and passive cooling; in the next chapter, we will discuss how thermal mass can reduce peak loads in an air-conditioning system. In this chapter on the thermal envelope, we will discuss how thermal mass can reduce heat gain in certain climates.

The time-lag property of materials can be used to reduce both the peak load and the total heat gain during the summer. Sections 3.18 and 3.19 explained the basic principles behind this phenomenon. The graph in Figure 15.11a shows the time it takes for a heat wave to flow through a wall or roof. The length of time from when the outdoor temperature reaches its peak until the indoor temperature reaches its peak is called the time lag. The graph also shows how the indoor-temperature range is much smaller than the outdoor-temperature range in part because of the moderating effect of the mass. Traditional buildings in hot and dry climates were usually built of stone, soil, or adobe (Fig. 15.11b).

To help choose the appropriate mass materials, Table 15.11 gives the time lag for 1 ft (30 cm) thick walls for a variety of materials. However, the time-lag property of materials should not be seen as a substitute for insulation but rather as an additional benefit of massive materials that are used for other purposes, such as heat storage and structural support.

Since all mass walls should have insulation, the question is where should the insulation be relative to the mass. For the benefits of time lag, it does not matter. However, for the benefits of passive solar, night-flush cooling, and peak load reduction, the mass should be on the indoor side of the insulation. The only exception would be a small part of the mass if used as the exposed weather screen (Fig. 15.11c).

The importance of light colors in reducing heat gain should not be forgotten. After all, time lag largely postpones heat gain, while light colors significantly reduce the heat gain.

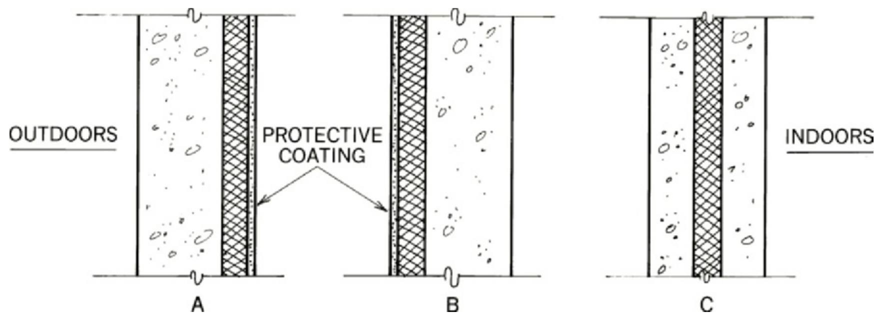


Figure 15.11c The placement of mass relative to the insulation is not critical in regard to time lag, but is important for other applications. (A) Mass on outside: good for fire and weather resistance and good for appearance. (B) Mass on inside: good for night-flush cooling, passive solar heating, and peak air-conditioning load reduction. (C) Mass sandwich: for some of the benefits of both A and B. However, maximize the mass on the indoor side of the insulation.

Rules for Thermal Mass

1. Never use thermal mass without insulation.
2. Mass on the indoor side of the insulation is best.
3. Do not insulate the mass from the indoors.
4. Since concrete has a high embodied energy content, it should provide as many benefits as possible.

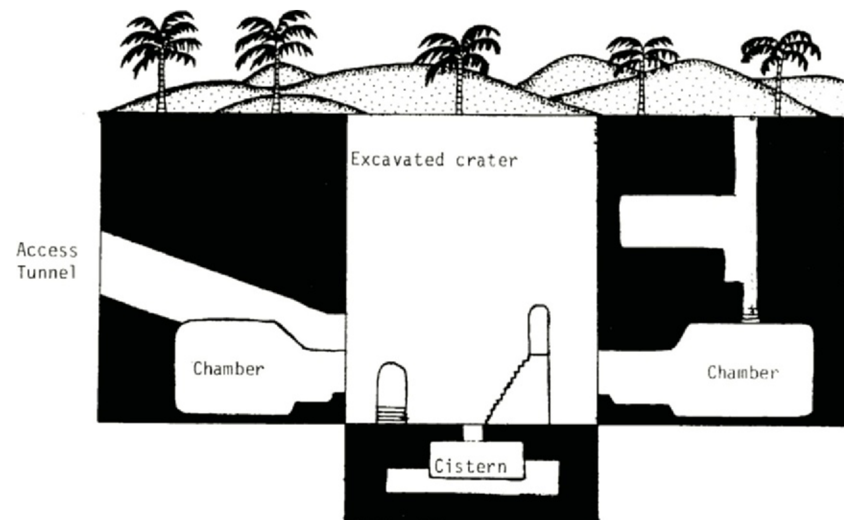
Mass is most valuable on the indoor side of the insulation!

15.12 EARTH SHELTERING

A survey of indigenous underground dwellings around the world shows that most are found in hot and dry climates. In Matmata, Tunisia, chambers and a central courtyard are carved out of the local sandstone, and access to the 30 ft (9 m) deep dwellings is by an inclined tunnel. Because of the dry climate, neither flooding nor condensation is a problem. More than 20 ft (6 m) of rock provides sufficient insulation, time lag, and heat-sink capability to create thermal comfort in the middle of a desert (Fig. 15.12a).

To understand the benefits of earth sheltering, one must understand the thermal properties of soil and rock. First, one must recognize that the insulating value of earth is very poor. It would take about 1 ft (30 cm) of dry soil to have the same R-value as 1 in. (2.5 cm) of wood, and it would take more than 10 ft (3 m) of earth to equal the R-value of an ordinary insulated stud wall, and even more if the soil were wet. Thus, earth is usually not a substitute for insulation. What, then, is the main benefit of earth in controlling the indoor environment?

Because of its massiveness, earth offers the benefits of time lag. In small amounts, the soil can delay



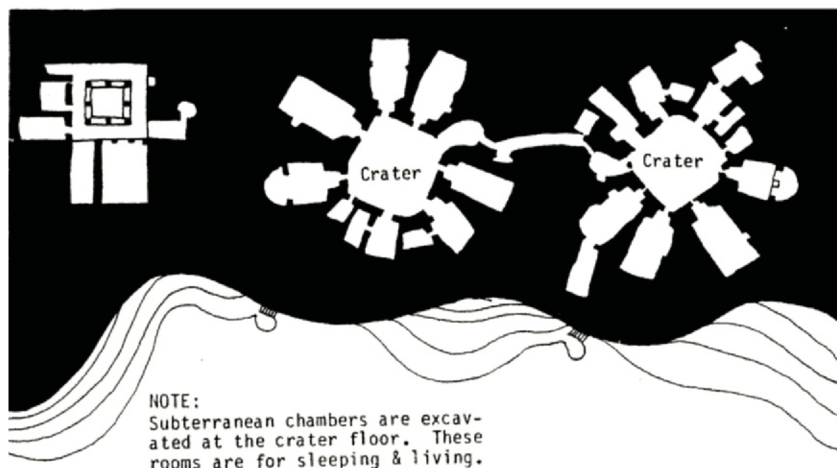


Figure 15.12a In Matmata, Tunisia, chambers and courtyards are cut from sandstone, which functions as both a heat sink and insulation. (From *Proceedings of the International Passive and Hybrid Cooling Conference*, Miami Beach, FL, Nov. 6–16, 1981. © American Solar Energy Society, 1981.)

and reduce the heat of the day just as massive construction, mentioned previously, does. In large quantities, the time lag of soil is about six months long. Thus, deep in the earth (about 20 ft [6 m] or more), the effect of summer heat and winter cold is averaged out to a constant steady-state temperature that is about equal to the mean annual temperature of that climate (see Fig. 10.14a). For example, at the Canadian border, the deep-earth temperature is about 45°F (8°C), while in southern Florida it is about 80°F (27°C) all year. See also the map in Figure 10.14b for deep-ground temperature throughout the United States.

The ground is, therefore, cooler than the air in summer and warmer than the air in winter. This is a much milder environment than a building experiences aboveground. But the closer one comes to the surface, the more the ground temperature is like the outdoor air temperature. Consequently, the deeper the building is buried in the earth, the greater the thermal benefits. In much of the country, the earth can act as a heat sink to give free cooling, because the deep-earth temperature is sufficiently lower than the comfort zone. Also, the heating load is greatly reduced because the deep-earth temperature is much higher than the winter outdoor air temperature.

There are, however, a number of important implications for underground construction. The biggest problems come from water. Thus, never build below the water table, and avoid wet and humid locations. Have a foolproof gravity-based way of draining storm water. Keep in mind that wet regions with soils that drain poorly require elaborate waterproofing efforts. Furthermore, in humid climates, condensation can form on the cool walls, causing mold and mildew.

Structural problems increase with the amount of earth cover. The main structural loads to be considered are of three types: weight of earth on roof, soil pressure on walls, and hydrostatic pressure on walls and floor.

Other challenges include providing for exit requirements (code) and the psychological needs of people. For example, most people want and need a view of the outdoors.

Where these problems can be solved, earth-sheltered buildings can offer substantial benefits, the greatest of which is security. By its very nature, an earth-sheltered building will be low to the ground and have a substantial structural system. Thus, it offers good protection against such forces as violent storms (tornadoes, hurricanes, lightning), earthquakes, vandalism, bombs (fallout shelter), temperature extremes, and noise (highway or airport) (Fig. 15.12b). In densely populated areas, the greatest benefit might be the retention of the natural landscape (Fig. 15.12c). Finally, from a heating and cooling point of view, these buildings are very comfortable and require substantially less energy than conventional buildings. For example, an underground factory in Kansas City required only one-third the heating and only one-twelfth the cooling equipment of a comparable aboveground building. Thus, earth sheltering also provides security from energy outages, shortages, and price increases.

There are four major schemes for the design of earth-sheltered buildings. The below-grade scheme offers the greatest benefits but also has the greatest liabilities (Fig. 15.12d). This type is usually built around sunken atriums or courtyards. The problem of flooding from storms can be partially solved by covering the atriums with domes. In the summer, the earth can act as a substantial heat sink and in the winter as an excellent buffer against the cold.

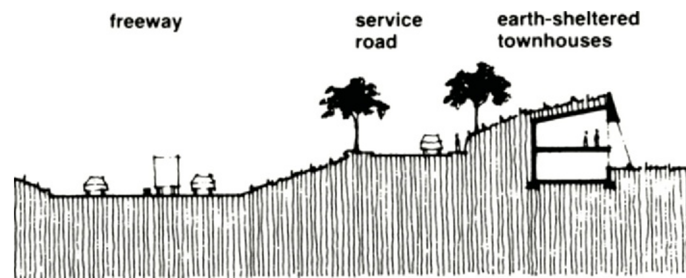


Figure 15.12b In densely populated areas, earth sheltering can help maintain the natural environment as well as protect from noise. (From *Earth Sheltered Housing Code: Zoning and Financial Issues*, by Underground Space Center, University of Minnesota. HUD, 1980.)

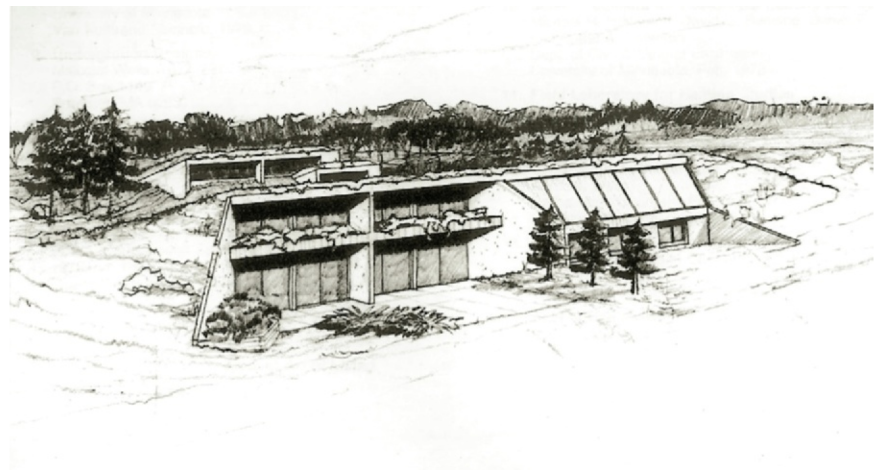


Figure 15.12c Earth-sheltered design helps preserve the natural landscape. ("Design for an Earth Sheltered House." Architect: Carmody and Ellison, St. Paul, MN. From *Earth Sheltered Housing Code: Zoning and Financial Issues*, by Underground Space Center, University of Minnesota. HUD, 1980.)

When an earth-sheltered structure is built on sloping land, the at-grade scheme is often the most advantageous, since water drains naturally, and there is easy access for people, light, and views (Fig. 15.12e). If built on a south slope, close to 100 percent passive solar heating is possible because of both the small heat loss and large thermal-storage mass of the earth.

On flat land, a mound of earth can be raised to protect a building that is built above grade (Fig. 15.12f). This scheme works well in hot and dry climates where time lag from day to night is very helpful.

Finally, one should consider the berm-and-sod-roof scheme when many openings are required for light and ventilation (Fig. 15.12g). However, the thermal benefits of earth berms are minimal except on west orientations in hot climates and north orientation to deflect the cold wind in cold climates (Fig. 15.12h). Likewise, sod roofs (vegetated roofs) help only a little in cold climates but can significantly reduce the summer heat gain through the roof. Just 1 to 2 ft (30 to 60 cm) of earth will furnish some daily time lag to reduce the overheating in hot and dry climates. Plants growing on the sod roof or berm will cool the earth by both shading and transpiration.

If berms are to have any benefit, they must be as continuous as possible. Each penetration of the berm is a major weakness, because heat flows in a three-dimensional pattern, as shown in (Fig. 15.12i). A cut in the berm creates a thermal weakness not only at the exposed wall but also in adjacent parts of the wall (Fig. 15.12j). Because of this heat short-circuiting, there should be as few penetrations as possible in any earth cover.

Although many factors determine the appropriateness of earth sheltering, one of the most important is climate. Earth sheltering is most advantageous in hot and dry climates and in regions that have both very hot summers and very cold winters. It is least advantageous in hot and humid regions, where water and mildew problems are common and where natural ventilation is a high priority.

The map and key in Figure 15.12k give a more detailed breakdown of regional suitability of earth sheltering.

Rules for Earth Sheltering

1. Never build below or near the water table.
2. Use a gravity-based foolproof system for drainage.

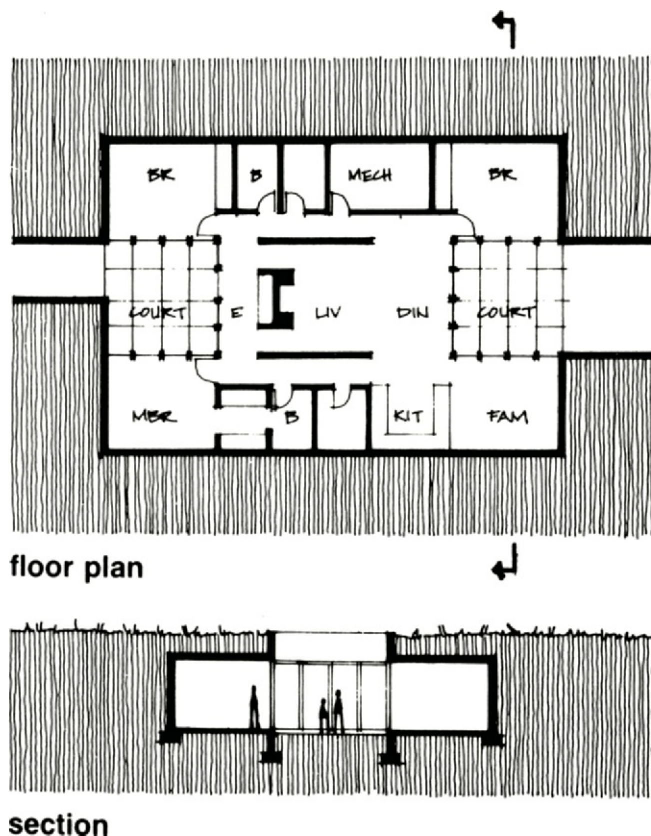


Figure 15.12d Below-grade scheme: Rooms are arranged around one or more atriums. Drainage and fire exits are major considerations. (From *Earth Sheltered Housing Code: Zoning and Financial Issues*, by Underground Space Center, University of Minnesota. HUD, 1980.)

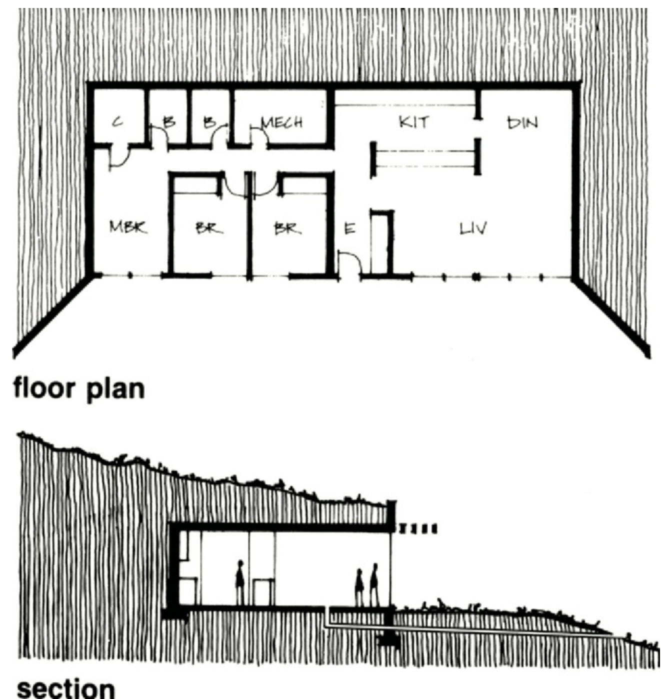


Figure 15.12e At-grade scheme: Drainage, egress, and views are all very good for an earth-sheltered structure built at grade on a slope. (From *Earth Sheltered Housing Code: Zoning and Financial Issues*, by Underground Space Center, University of Minnesota. HUD, 1980.)

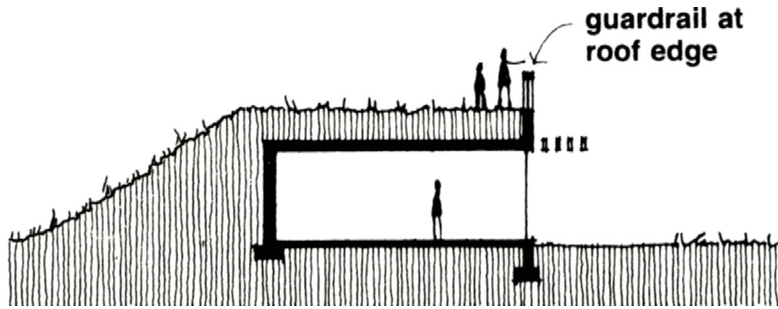


Figure 15.12f Above-grade scheme: On flat land with poor drainage, an artificial mound might be the best strategy. (From *Earth Sheltered Housing Code: Zoning and Financial Issues*, by Underground Space Center, University of Minnesota. HUD, 1980.)

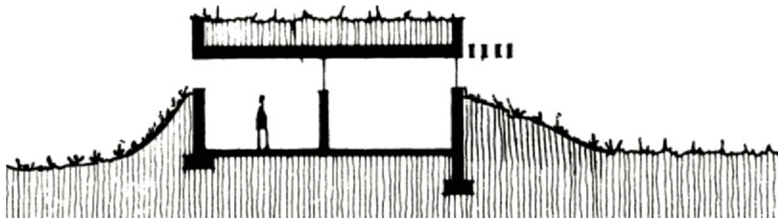


Figure 15.12g Berm-and-sod-roof scheme: When natural ventilation, daylight, and views are important, berms are appropriate. Sod roofs (vegetated roofs) are best for protection from summer heat. (From *Earth Sheltered Housing Code: Zoning and Financial Issues*, by Underground Space Center, University of Minnesota. HUD, 1980.)



Figure 15.12h This highway rest area in Idaho uses earth berms both to deflect the northerly winter winds and to deflect the hot summer sun from the east and west facades. South glazing collects winter sun, while a south-facing overhang shades the south glazing from the summer sun.

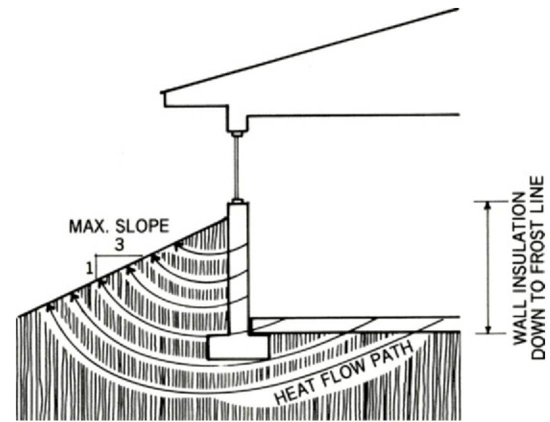


Figure 15.12i Since heat flows through earth in the radial pattern shown, the heat-flow path is quite long at the base of the wall and through the slab edge. Insulation (not shown for clarity) should, therefore, be thickest at the top of the earth-bermed wall.

3. It is most appropriate for climates with extreme temperatures.
4. It is least appropriate in wet, humid, and mild climates.
5. The ideal site is on a south-facing hillside where winter heating is needed and on a north-facing hillside where heating is not needed.

Regional Earth Tempering Issues (see Fig. 15.12k)

A. Cold, cloudy winters maximize the value of earth tempering as a heat conservation measure. Cool soil and dry summers favor subgrade placement and earth cover, with little likelihood of condensation.
B. Severely cold winters demand major heat conservation measures, even though more sunshine is available here than on the coast. Dry summers and cool soil favor earth-covered roofs and ground coupling.
C. Good winter insulation offsets the need for extraordinary winter heat conservation, but summer benefit is more important here than in zone B. Earth cover is advantageous, the ground offers some cooling, condensation is unlikely, and ventilation is not a major necessity.
D. Cold and often cloudy winters place a premium on heat conservation. Low summer ground temperatures offer a cooling source, but with possibility of condensation. High summer humidity makes ventilation the leading natural summer climate control strategy. An aboveground superinsulated house designed to maximize ventilation is an important competing design approach.
E. Generally good winter sun and minor heating demand reduce the need for extreme heat conservation measures. The ground offers

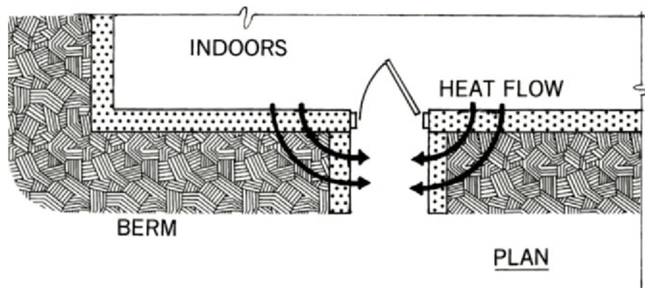


Figure 15.12j Minimize berm penetration because each opening is a major source of heat loss.

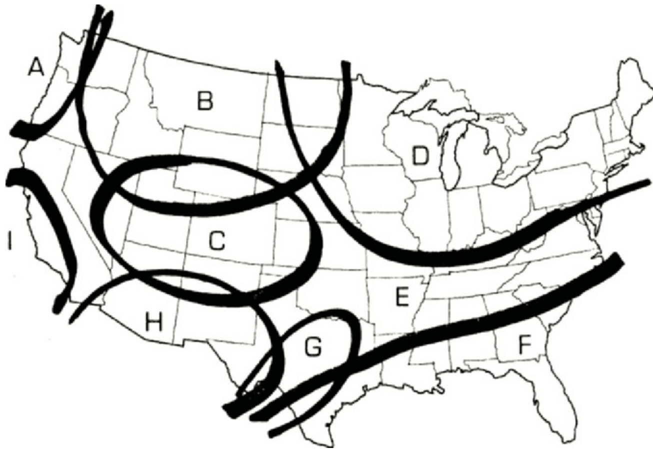


Figure 15.12k A summary of regional issues in regard to suitability of earth sheltering is shown. (From *Proceedings of the International Passive and Hybrid Cooling Conference*, Miami Beach, FL, Nov. 6–16, 1981. © American Solar Energy Society, 1981.)

protection from overheated air, but it does not offer much cooling potential as a heat sink. The primacy of ventilation and the possibility of condensation compromise summer benefits. Quality of design will determine actual benefit realized here.

F. High ground temperatures. Persistent high humidity levels largely negate the value of roof mass and establish ventilation as the only important summer cooling strategy. Any design that compromises ventilation effectiveness without contributing to cooling may be considered counterproductive.

G. This is a transition area between zones F and H, comments concerning which apply here in degree. The value of earth tempering increases moving westward through this zone and diminishes moving southward.

H. Summer ground temperatures are high but relatively much cooler than those of air. Aridity favors roof mass, reduces need for ventilation, and eliminates concern about condensation. Potential for integrating earth tempering with other passive design alternatives is high.

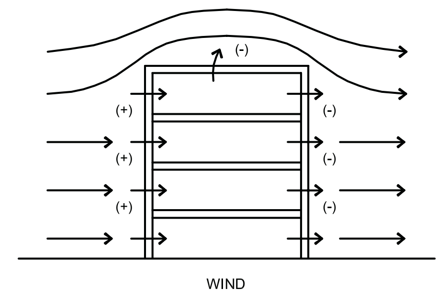
I. Extraordinary means of climate control are not required due to the relative moderateness of this zone. Earth tempering is compatible with other strategies, with no strong argument for or against it.

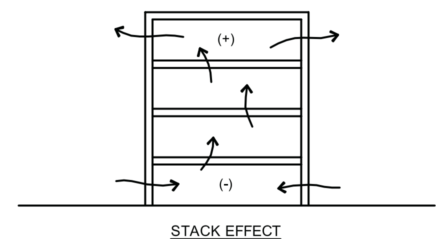
15.13 INFILTRATION AND VENTILATION

In a poorly constructed house with no weatherstripping on doors and windows, more than 50 percent of the heat loss can be due to infiltration. Good, tight construction techniques with quality weatherstripped windows and doors can reduce the loss from infiltration to about 30 percent of the total building heat loss, but that is still far too large for a sustainable world. Thus, a well-designed air-barrier system is needed that can reduce the infiltration losses to less than 5 percent.

Infiltration is the unplanned introduction of outdoor air through windows, doors, or cracks in the construction. It is caused by wind pressure, the stack effect, excessive ventilation by exhaust fans, and the action of chimneys exhausting room air that is used for combustion in fireplaces or furnaces.

In winter, as dry cold air enters the building, an equal amount of warm, moist air leaves (Fig. 15.13a). As a result, latent as well as sensible heat is lost. In summer, hot, moist air infiltrates and cool, dry air is lost.





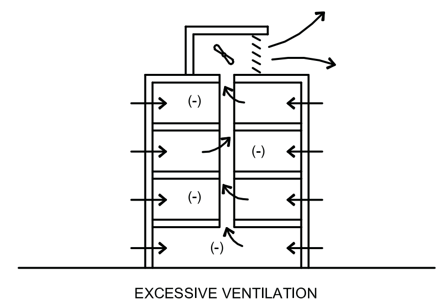


Figure 15.13a Infiltration is caused by the wind, stack effect, and improper ventilation. The taller the building, the greater the infiltration due to both the wind and the stack effect (see also Section 10.5). Proper ventilation, unlike what is shown, often causes the building to have a positive pressure, which prevents infiltration of outside air. Using indoor air for combustion can create the same problem as excessive mechanical ventilation.

Consequently, the cooling load is also both latent and sensible in all but very dry climates.

Infiltration is controlled first by avoiding windy locations or by creating windbreaks. Minimizing doors and operable windows helps, but more important is the seal. A poorly fitted, unweatherstripped window has an infiltration rate five times as great as that of an average-fit weatherstripped window. Quality modern windows allow very little infiltration, as can be verified by their air leakage rating, which is determined by the National Fenestration Rating Council.

In buildings where doors are opened frequently, a vestibule can cut infiltration by 60 percent and revolving doors can cut infiltration by an amazing 98 percent (Fig. 15.13b).

Because ordinary construction systems have many cracks and porous components, a separate wind barrier is required. A 2005 study by the National Institute of Standards and Technology (NIST) shows that air-barrier systems can reduce air leakage by 85 percent. The most common kind of wind barrier has been a woven fabric that comes in 9 or 10 ft (about 3 m) rolls in order to minimize the number of joints. Now there are also spray-on or paint-on wind barriers applied to the sheathing either in the field or in the factory. To allow for movement, joints must be taped with a flexible material. Besides greatly reducing infiltration, wind barriers also block liquid water from passing through the wall. However, most are also designed to be permeable to water vapor so that walls can dry out if water should get behind the wind barrier.

Since a building cannot be low energy if there is much infiltration, it is important to measure its air tightness. Increasingly, blower door testing is required to certify air tightness and to find the hidden gaps in the "air control boundary." The test consists of setting up one or more blowers in doorframes of exterior doors (Fig. 15.13c). The fans are run until a predetermined pressure difference has been achieved. The airflow then needed to maintain that pressure indicates the size of air leakage. Smoke streams and infrared photography can be used to help locate the air leaks. The infiltration rate is often given in terms of air changes per hour (ACH). Table 15.13 shows common air change rates in traditional and modern low energy buildings.

When a building becomes airtight, additional actions must be taken to prevent a new set of problems. Fireplaces and gas heating appliances could be starved for air,

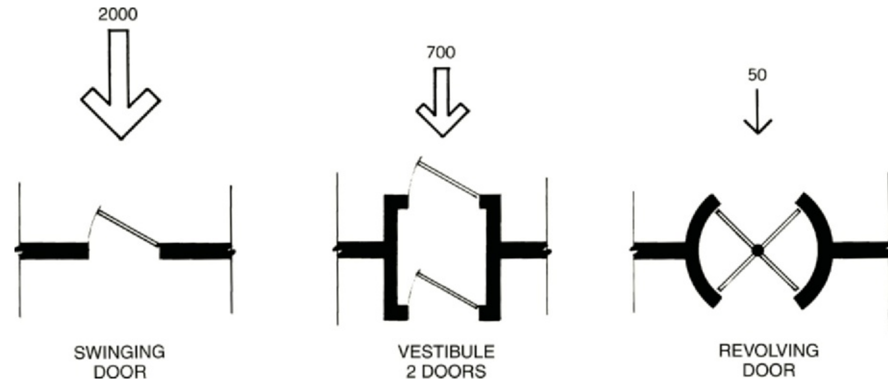


Figure 15.13b The number indicates the cubic feet of air infiltrating due to one door operation.



Figure 15.13c A sustainable building must have minimal infiltration, and that can only be established with a blower door test.

Table 15.13 Air Changes per Hour (ACH)

By Building Type, Code, or Certification	ACH*
Old, very leaky house	8+
Old leaky house	4+
Typical older house	2
Well-constructed older house	1
Standard modern house	0.5–1
Extremely tight new construction	less than 0.35
International Residential Code	max. 7
LEED	max. 4
Energy Star 2.5 and 3	max. 4
International Energy Conservation Code (IECC)	max. 3
Passivhaus	max. 0.6
ASHRAE residential	0.1–2.0
ASHRAE commercial	0.5–2.0

*At a pressure of 50 pascals

odors and moisture could build up, and eventually a shortage of oxygen for breathing could result. Often, there is also a problem of indoor air pollution caused by using toxic building materials, furniture, or cleaning materials. Thus, besides avoiding the use of toxic materials, provisions must be made to bring in sufficient fresh air in a controlled manner. This is called ventilation and is described in more detail in the next chapter on mechanical equipment.

15.14 MOISTURE CONTROL

Excess moisture not only adds to the cooling load but also can cause serious problems in buildings. The structure can rust or rot, the insulation can become useless, and the paint can peel. Indoors, windows can fog up, and mold can grow, causing health problems. Moisture can come from the outside or be generated indoors, and can enter the building envelope as either water or water vapor that then condenses. Although moisture in vapor form can cause mold to grow, it is mainly water in the liquid state inside the building fabric that causes most problems. Moisture can enter the building envelope in four ways: bulk moisture, capillary action, air leakage, and vapor diffusion.

1. Bulk moisture is liquid water that enters through holes, cracks, or gaps, and it is usually rainwater driven by gravity and wind. Proper design and quality construction will minimize the amount of bulk moisture penetrating the building skin. Every wall should have a drainage plane or drainage cavity created by a rainscreen (siding, brick veneer, etc.) on the outside and, on the inside, a wind barrier to block liquid water as well as the wind (Fig. 15.14a). Thus, any water that gets behind the rainscreen will flow down the cavity and be diverted back out by flashing. When the rainscreen is not masonry, the cavity can be created by vertical furring (spacer) strips or by textured wind barriers that create vertical channels large enough to prevent capillary action (Fig. 15.14b).
2. Capillary action moves liquid water through porous materials and tiny holes by the surface tension on the water. The effect is strong enough to move water vertically against gravity. Capillary action is controlled primarily by fully sealing porous materials and tiny holes with some material, such as the asphaltic waterproofing on a concrete foundation wall.
3. Air leakage carries water vapor through holes and cracks in the building envelope by the action of the wind, fans, or the stack effect. The wind barriers described in the previous section are designed to minimize air leakage in the building envelope.

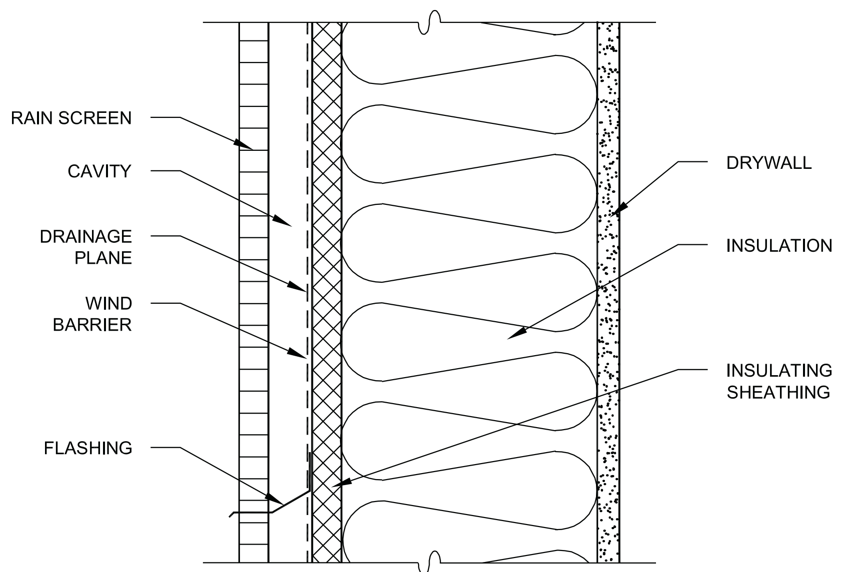


Figure 15.14a Every wall should have a drainage plane (drainage cavity) faced with a wind barrier to drain water that gets behind the rainscreen (siding, brick veneer, etc.).

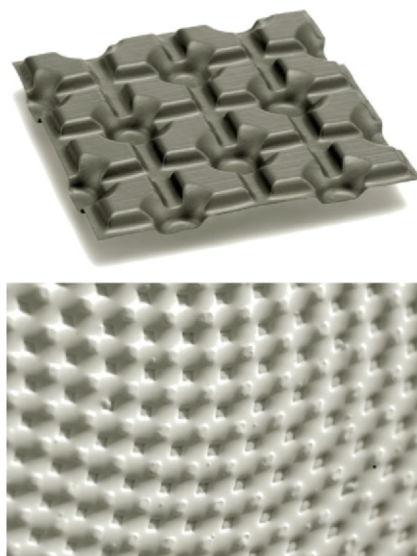


Figure 15.14b Water-resistant barriers in walls must not only stop water transmission but also allow water to drain down and out. Some water-resistant barriers create their own drainage channels (Vortec on the bottom and Delta-Dry on the top). (Valéron Vortec is a trademark of Valéron Strength Films, an ITW company. Cosella–Dörlken 2006.)

4. Water vapor also enters the building fabric because of vapor diffusion, which is driven by a difference in vapor pressure. Water vapor moves from a higher concentration of moisture (high vapor pressure) to a lower concentration (low vapor pressure). Generally, that would be outward through the wall in the winter and inward in humid climates in the summer. Recent research has shown that vapor diffusion is much less of a problem than air leakage.

Water entering the building fabric through bulk-moisture flow is immediately ready to cause problems, but water vapor entering through air leakage or vapor diffusion will primarily cause problems if condensation occurs in the wall or roof. Condensation will occur if part of the construction is colder than the dew-point temperature of the moist air.

Condensation inside the building envelope in winter can be prevented by not allowing the indoor air to be cooled to its dew point, also known as the saturation point, condensation point, or 100 percent relative humidity point. In regard to the building envelope, this phenomenon can be better understood with the concept of the thermal gradient, in which the temperatures across a wall (roof, etc.) are graphed on top of a drawing of the wall (roof, etc.), as shown in Figure 15.14c. Thus, it is easy to determine the temperature in any part of the construction. For example, the temperature on the indoor side of the fiberglass batts in Figure 15.14c is 65°F (18°C), while on the outdoor side of the batts it is about 19°F (7°C). As the indoor air slowly moves through the wall, its temperature drops, as the thermal gradient indicates. As the indoor air cools, its relative humidity (RH) will increase (see again Section 4.5). Eventually, it will reach 100 percent RH, which is also known as the dew point." At this point, water condenses out of the air and wets the insulation like dew forming on grass.

A major concern of building scientists is how building materials and envelope systems behave when exposed to different combinations of moisture and heat (see Sidebox 15.14A).

Rules to prevent condensation in the building envelope:

1. Use a wind barrier that reduces humid indoor air in the winter and humid outdoor air in the summer from entering the thermal envelope. Keep in mind that air leakage is a problem one hundred times greater than moisture diffusion.

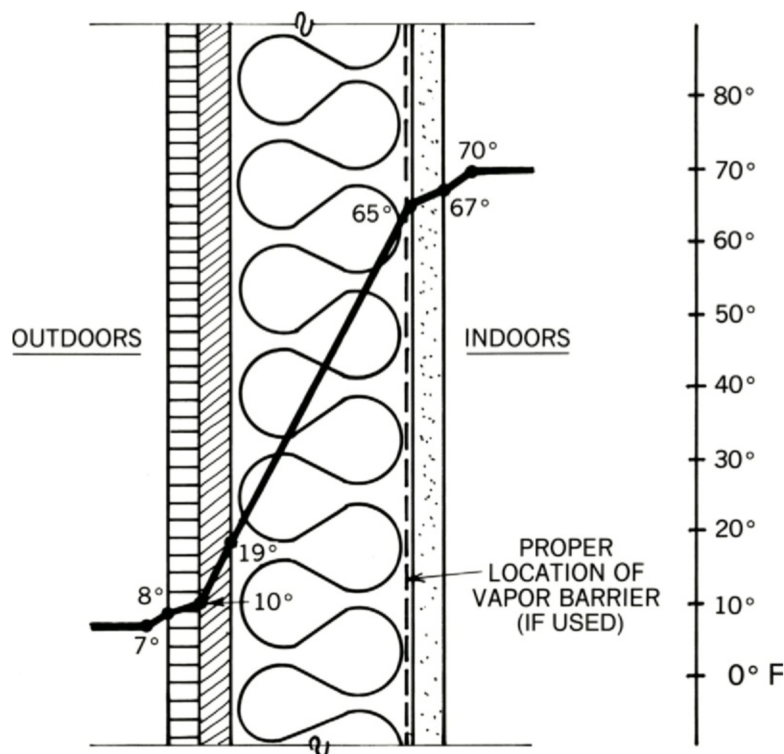


Figure 15.14c The graph of the thermal gradient, which is superimposed on a wall detail, clearly shows the temperature at each layer inside the construction. The dew-point temperature of the air determines if and where in the wall condensation will occur. Vapor barriers are recommended only in very cold climates.

SIDEBOX 15.14A

Hygrothermal Behavior of Materials

The complexity of the hygrothermal (water and heat) behavior of materials can be best explained by an example. A brick wall will absorb a fair amount of water during an extended rainstorm. When the sun comes out and heats the brick wall, the moisture near the surface starts to evaporate. Although the brick surface will dry out, the resulting vapor pressure also pushes the remaining water farther into the interior, with potentially negative consequences.

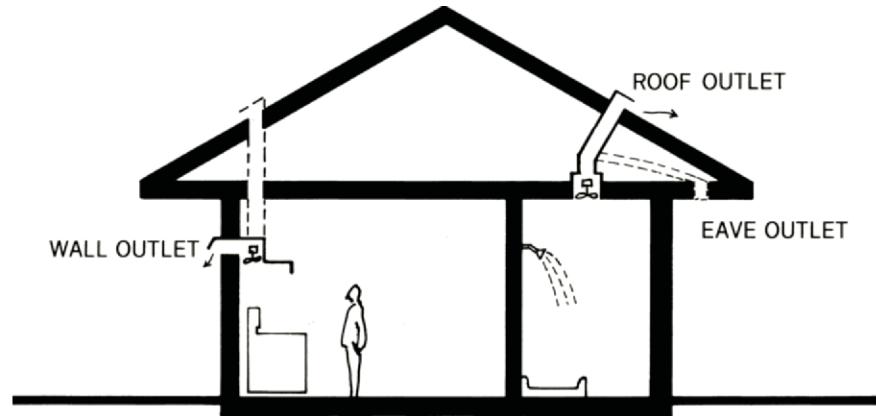


Figure 15.14d Moisture should be exhausted at the source. Vent it outside and never into the attic.

2. Control indoor humidity with exhaust fans in moisture-producing areas such as bathrooms and kitchen stoves (Fig. 15.14d). If the indoor RH is still over 60 percent, use a dehumidifier.
3. Use tight construction to minimize water vapor from entering the building envelope.
4. Consider using insulation that is not porous. Water vapor will not condense in closed cell foam insulation because the water vapor can't penetrate the insulation. One of the advantages of SIP and insulated metal panels is that there is no condensation problem. In ordinary construction, a thick layer of insulating sheathing can also prevent condensation in all but very cold climates.
5. In very cold climates, like that of Canada, use a vapor barrier in the location shown in Figure 15.14c. See Sidebox 15.14B for the permeability of various vapor barriers.
6. In cold climates, like that of the northern United States, consider using a "smart" vapor barrier (e.g., MemBrain) whose permeability increases with the RH and therefore is less likely to trap moisture.
7. In most climates, do not use a vapor barrier because it is likely to trap moisture and prevent the building envelope from drying. A basic rule is never to have two vapor barriers, and since the insulating sheathing acts as a vapor barrier, there should be no other.
8. Design the building envelope so that it can dry out when it gets wet, which it will. If it dries quickly enough, no or little damage will occur.
9. Use hygric buffer materials that have a large moisture-storage capacity, because the stored water is then not available to cause rust, rot, or mold growth. Wood and masonry are excellent hygric (water) buffers, because they dry out between rains.
10. Attics, roofs, and sometimes walls should be vented to prevent water damage (Fig. 15.14e). These vents have the additional benefit of allowing hot air to escape in the summer. See Table 15.14 for recommended attic vent areas. For best results, half of the vent area should be in the soffit and half at the ridge. Continuous ridge vents, as shown in Figure 15.14f, are very effective and highly recommended, as are aerodynamically designed roof vents (see Fig. 10.6u). However, electrically powered roof vents are generally not economical.
11. In basements and earth-sheltered buildings, moisture is avoided by good drainage around the walls and carefully installed waterproofing. In buildings with crawl spaces, the soil should be covered with a polyethylene vapor barrier and the crawl space should be vented (see Table 15.14).

SIDEBOX 15.14B

The term "vapor barrier" can refer to either a membrane specifically installed in the building envelope or to any part of the construction that can retard the movement of water vapor. The permeability of a vapor barrier is given in perms, where zero represents complete impermeability. Codes and other construction literature often divide vapor barriers into three classes of permeability, as shown in Figure 15.14h.

Rules for Bulk Water Control

1. Drain, drain, drain: Get rainwater off and away from the building. Use design strategies to avoid water problems (Fig. 15.14g).
2. Drainage plane: Always have a drainage plane or cavity in walls.

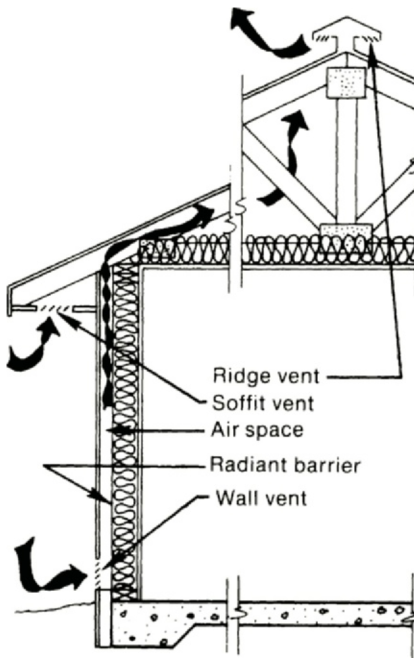


Figure 15.14e Make sure that the airflow from soffit to ridge or gable vents is not blocked by the ceiling insulation. When wall vents are used, they act as a passive cooling technique in addition to moisture control. (From *Cooling with Ventilation*. Golden, CO: Solar Energy Research Institute, 1986 (SERI/SP-273-2966; DE8601 701).)

Table 15.14 Recommended Vent Areas

Space Vented	Vent Area/Floor Area
Crawl space*	
No ground cover	1/150
With vapor barrier on ground	1/1500
Attic†	
No ceiling vapor barrier	1/150
With ceiling vapor barrier	1/300

*At least one vent near each corner of crawl space.
†Half at or near the ridge and half at the soffit.

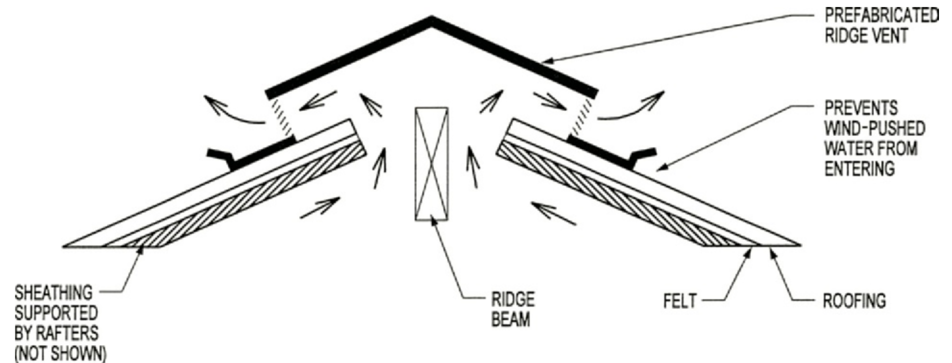


Figure 15.14f Continuous ridge vents efficiently evacuate hot and/or moist air by the combined action of the stack, Bernoulli, and venturi effects (See Fig. 10.5l). Ridge vents must be carefully designed to prevent wind-blown water from entering the building.

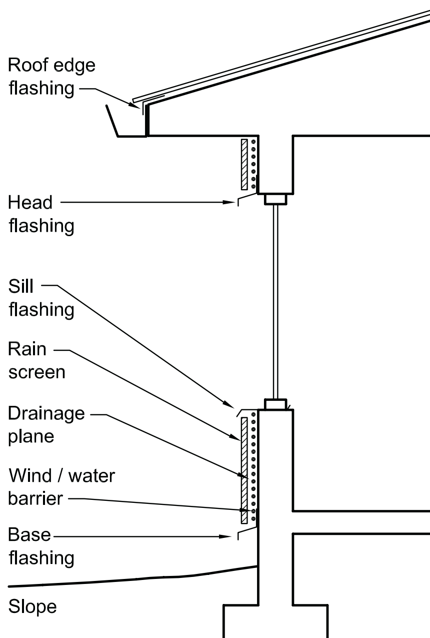


Figure 15.14g Always have a positive way to drain bulk water. Use drainage planes to keep water from entering and flashing to drain it back out if it gets behind the wind/water barrier.

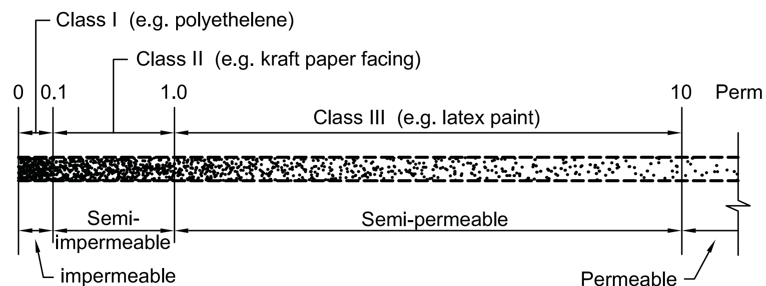


Figure 15.14h The permeability of vapor barriers is described in perms, with 0 representing totally impermeable.

15.15 RADON

The U.S. surgeon general identified radon as the second leading cause of lung cancer after cigarettes. The element radon is a radioactive gas generated in the ground by the radioactive decay of uranium. Because it is a gas, it moves slowly up through the soil into the atmosphere or into a building. Because the stack effect or a faulty air-conditioning system can create negative pressure, radon can be sucked into a building. This problem is most severe with crawl spaces or slabs-on-grade that have many cracks, holes, or joints. Since there is no foolproof method for predicting the absence of radon, crawl spaces should always be vented and slabs well built and sealed. If radon is

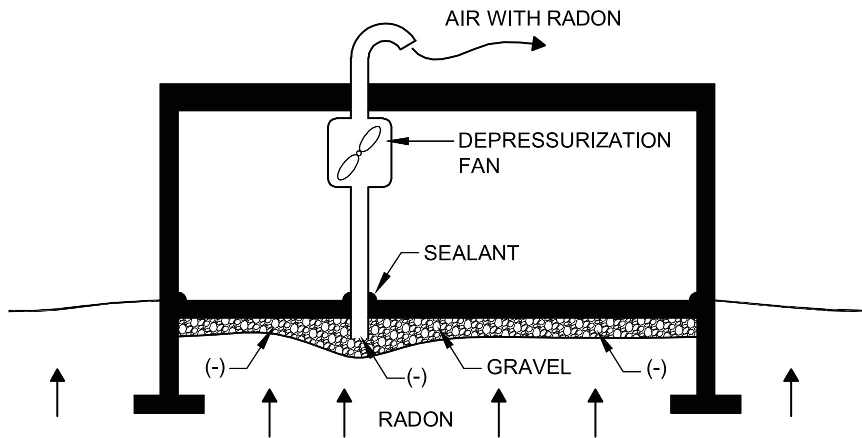


Figure 15.15 When radon is expected or found to be present, any or all of the following should be performed: all slab penetrations should be sealed particularly well, the building's mechanical equipment should be run at a positive pressure, and the under-slab gravel should be depressurized.

suspected because of information available before construction or is discovered by testing after the building is completed, then three additional techniques are available: (1) provide extra sealing of radon entry routes; (2) pressurize the building; and (3) depressurize the under-slab gravel (Fig. 15.15).

15.16 APPLIANCES

Although not part of the thermal envelope, appliances can add significantly to the cooling load. Appliances vary greatly in the amount of energy they consume and, therefore, the amount of heat they give off. The cost of inefficient appliances is double, since first one must pay for using unnecessary energy and then pay again for extra cooling to have the unnecessary heat removed from the building in the summer.

By law, some appliances, like refrigerators, must state their efficiency with an energy efficiency ratio (EER) label. To further help in selecting efficient appliances, the U.S. Environmental Protection Agency (EPA) introduced the Energy Star program in 1992. Appliances that exceed minimum efficiency standards are given the Energy Star stamp of approval. Thus, only lights and appliances that have the Energy Star label should be bought or specified.

Figure 15.16 is included to help focus attention on those appliances that use the most energy in the home. In residences, hotels, schools, restaurants, prisons, and similar buildings, a great deal of energy is used to heat domestic hot water. All such buildings should use active solar systems to generate most of the hot water needed. As mentioned earlier, the lighting system is often a major energy user and, therefore, also a major source of heat gain. Thus, in all buildings, but especially nonresidential buildings, the lighting system should use daylighting and have lamps of high efficacy and luminaires of high efficiency. By choosing the more efficient appliances, consumers will encourage manufactures to create even more efficient devices.

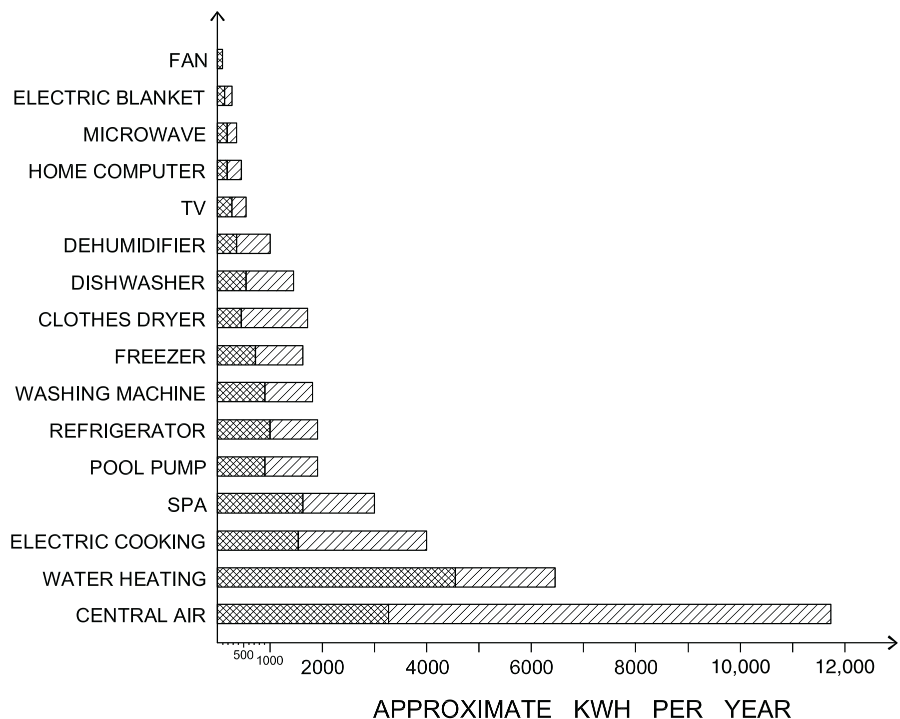


Figure 15.16 This chart shows the approximate annual use of electrical energy (kwh) by appliances in homes. After air-conditioning, water heating is the next largest consumer of energy in the home. As mentioned before, active solar collectors should produce hot water. Although the rest of the appliances use less energy each, together they are significant consumers of energy. Thus, always use the most efficient appliances possible. Because of the many variables, a range of energy use is given for each appliance.

15.17 CONCLUSION

All buildings should be sustainable, but to be sustainable they must be energy efficient, and to be energy efficient they must have an excellent thermal envelope that keeps the winter heat in and the summer heat out. Such buildings can cost less initially because their heating and cooling equipment is smaller, and they certainly cost less to operate, since their energy bills will be much lower. Not only will owners save money and society save valuable energy, but it is the morally correct thing to do. The future of the planet depends on it.

Besides minimizing climate change, high performing thermal envelopes also provide security in a more direct way. Their use is a key strategy in making a building resilient against such negative events as power outages and extreme weather.

This discussion on the techniques for keeping warm and staying cool finishes the discussion of that part of the heating, cooling, and lighting of buildings that is primarily in the domain of the architect. Although the mechanical heating and cooling systems discussed in the next chapter are mainly the responsibility of engineers, architects must still help to integrate these systems properly into the building. It is, therefore, vital for architects to have a general understanding of the mechanical systems.

KEY IDEAS OF CHAPTER 15

1. Designing the thermal envelope is part of the first tier of the three-tier design approach. The better the thermal envelope, the less heating and cooling will be required.
2. Thermography can be used to find holes or weak areas in the thermal envelope.
3. Heat is lost by transmission through walls, roof, floors, windows, and doors; by infiltration through cracks; and by purposeful ventilation.
4. Heat is gained from transmission, ventilation, solar radiation, appliances, lighting, and people.
5. In most cases, a compact design will use fewer resources than a spread-out, extended design.
6. The extra heating effect of sunlight on a wall or roof is accounted for by the **sol-air temperature**.
7. The **design-equivalent temperature difference** is used when the insulating effect of mass is also considered.
8. In hot climates, use surfaces with high solar reflectivity (albedo). White is the greenest color!
9. **Thermal planning** arranges building spaces in accordance with their heat and temperature needs as related to solar orientation.
10. Insulation materials consist primarily of very small air spaces separated by a material of low thermal conductivity.
11. Shiny metal surfaces are good radiant barriers because they have both high reflectivity and low emissivity. Radiant barriers are most advantageous under roofs in hot climates.
12. Large air spaces should not be used because their R-value is about the same as that of small air spaces. Large air spaces should be subdivided into as many small air spaces as possible.
13. Log cabins should not be built because they waste wood and have mediocre thermal resistance by modern standards.
14. Avoid creating heat bridges through the thermal envelope. Especially avoid exposed floor slabs and cantilevered balconies without thermal breaks.
15. Structural insulated panels (SIPs) and insulated metal panels (IMP) have both high thermal resistance and great structural strength.
16. Low-e, double-glazed (R-3) (RSI-0.5) windows should be the minimum standard in all but the mildest climates.
17. Use high-performance (R-4 and higher) (RSI-0.7 and higher) windows whenever possible. Use high SHGC windows on south walls.
18. Use selective low-e glazing when cool daylight is required.
19. Movable insulation over windows can reduce heat loss during winter nights and heat gain during summer days.
20. In hot climates with medium to large diurnal temperature ranges, i.e., dry to medium dry climates, massive walls will reduce the heat gain by the insulating effect of thermal mass. Insulation should be used nevertheless, and the mass should be on the indoor side of the insulation.
21. Earth sheltering is most appropriate in climates with very hot summers and very cold winters. It is least appropriate in wet and humid regions.
22. Use earth sheltering only when positive-gravity drainage is assured.
23. Vegetated (green) roofs are mainly beneficial in reducing heat gain.
24. Use a wind barrier on the indoor side of the drainage plane and a rainscreen on the outdoor side of the drainage plane.
25. Moisture can enter a building in four ways: bulk moisture, capillary action, air leakage, and vapor diffusion.
26. Use vapor barriers to prevent condensation inside walls only in very cold climates.

27. Avoid creating excess moisture. Use exhaust fans where large quantities of water vapor are produced.
28. Use eave, ridge, and gable vents to prevent moisture problems in the roof.
29. Use a ground vapor barrier to prevent moisture problems in crawl spaces.
30. Vent crawl spaces to prevent both moisture and radon problems. Use unvented insulated crawl spaces only if neither moisture nor radon is a problem.
31. Infiltration barriers should stop the wind but not water vapor.

References

Akbari, H., et al., eds. *Cooling Our Communities: A Guidebook on Tree Planting and Light-Colored Surfacing*. Washington, DC: EPA and DOE/ Lawrence Berkeley Laboratory, 1992 [Lawrence Berkeley Laboratory LBL-31587].

Environmental Building News, October 1998.

Watson, D., and K. Labs. *Climatic Design: Energy-Efficient Building Principles and Practices*. New York: McGraw-Hill, 1933.

Resources

Further Reading

(See the Bibliography in the back of the book for full citations.)

Boyer, L., and W. Grondzik. *Earth Shelter Technology*.

Brown, G. Z., and M. DeKay. *Sun, Wind and Light: Architecture Design Strategies*, 3rd ed.

Carmody, J., J. Christian, and K. Labs. *Builder's Foundation Handbook*.

Carmody, J. S. Selkowitz, and L. Heschong. *Residential Windows: A Guide to New Technologies and Energy Performance*, 3rd ed.

Carmody, J., S. Selkowitz, E. S. Lee, D. Arasteh, and T. Willmert, *Window Systems for High-Performance Buildings*.

Carmody, J., and R. Sterling. *Earth Sheltered Housing Design*.

Easton, D. *The Rammed Earth House*.

Franta, G., K. Anstead, and G. D. Ander. *Glazing Design Handbook for Energy Efficiency*.

Golany, G. *Design and Thermal Performance: Below Ground Dwellings in China*.

Grondzik, W., and A. G. Kwok. *Mechanical and Electrical Equipment for Buildings*, 12th ed.

Hestnes, A. G., R. Hastings, and B. Saxhof, eds. *Solar Energy Houses: Strategies, Technologies, Examples*.

Houben, H., and H. Guillaud. *Earth Construction: A Comprehensive Guide*.

King, B. *Buildings of Earth and Straw: Structural Design for Rammed Earth and Straw-Bale Architecture*.

Krigger, J. T. *Residential Energy: Cost Savings and Comfort for Existing Buildings*.

Kwok, A. G., and W. T. Grondzik. *The Green Studio Handbook: Environmental Strategies for Schematic Design*, 2nd ed.

Lstiburek, J. W. *Builder's Guide to Cold Climates: Details for Design and Construction*.

———. *Exemplary Home Builder's Field Guide*.

———. *Builder's Guide to Mixed Climates: Details for Design and Construction*.

Lstiburek, J. W., and J. Carmody. *Moisture Control Handbook: Principles and Practices for Residential and Small Commercial Buildings*.

Matus, V. *Design for Northern Climates: Cold-Climate Planning and Environmental Design*.

Norton, J. *Building with Earth: A Handbook*.

Steven Winter Associates. *The Passive Solar Design and Construction Handbook*.

Underground Space Center. *Earth Sheltered Housing Design: Guidelines, Examples, and References*.

U.S. Department of Housing and Urban Development. *Moisture-Resistant Homes: A Best Practice Guide and Plan Review Tool for Builders and Designers with a Supplemental Guide for Homeowners*. www.huduser.org.

Watson, D., and W. M. C. Labs. *Climatic Design: Energy-Efficient Building Principles and Practices*.

Organizations

(See Appendix K for full citations.)

Energy Efficiency & Renewable Energy (U. S. DOE) www.eere.energy.gov

Energy Efficient Building Association www.eeba.org

National Institute of Building Science, Building Enclosure, Technology, and Environment Council www.nibs.org/betec

Southface Energy Institute www.southface.org

Web-Based Sources

Air Leakage Guide, from the Building Technologies Program at the Energy Efficiency and Renewable Energy Division of the U.S. Department of Energy, www.energycodes.gov

CHAPTER 16

MECHANICAL EQUIPMENT FOR HEATING AND COOLING

The chief source of problems is solutions.
Eric Sevareid, 1970, as quoted in Stan Cox,* Losing Our Cool *(p. 15), on the worldwide problem of air-conditioning.

It is not a question of air conditioning versus sea breezes, or fluorescent tubes versus the sun. It is rather the necessity for integrating the two at the highest possible level.
James Marston Fitch
American Building: The Environmental Forces That Shape It, *1972*

16.1 INTRODUCTION

In most buildings, mechanical equipment (tier three) is required to carry the thermal loads remaining after the techniques of heat retention or rejection (tier one) and passive heating or cooling (tier two) have been applied (Fig. 16.1). With the proper design of the building, as described in previous chapters, the size and energy demands of the heating and cooling equipment can be quite small. Since the heating and cooling equipment is bulky and must reach into every space, it is an important concern for the architectural designer.

Since the history of heating is much longer than the history of cooling, and since it is simpler to understand, it is discussed first.

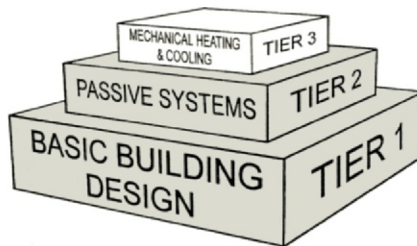


Figure 16.1 The heating and cooling needs of a building are best and most sustainably achieved by the three-tier design approach. This chapter discusses tier three (mechanical equipment).

16.2 HEATING

Conceptually, heating is very simple: a fuel is burned and heat is given off. The simplest heating system of all is a fire in the space to be warmed.

Until the twelfth century, it was the almost universal practice—even in royal halls—to have a fire in the center of the room with the smoke exiting through the roof or a high window (Fig. 16.2a). The central open fire was not only an efficient heater, it also provided light and a cooking fire. However, the smoke and flying cinders made the concept of cleanliness inconceivable. Around the Mediterranean Sea and in some other warm climates around the world, small portable heaters, such as **charcoal braziers**, were popular (Fig. 16.2b). The Japanese hibachi is a similar device. A real exception to these primitive heating systems was the Roman **hypocaust**, where warm air from a furnace passed under a floor and up through the walls (Fig. 16.2c). Traditional Korean buildings use a similar under-floor heating system. While the Roman hypocaust was only for the rich or the public baths, in Korea it was used by rich and poor alike. The rich had separate heating fires, while the poorer people directed the heat and smoke of their cooking fires under their bedrooms (Fig. 16.2d).

In Europe the fireplace came about with the invention of the chimney in the twelfth century A.D.



Figure 16.2a Some royal halls were still heated by an open fire as late as A.D. 1300. The hall of Penhurst Place. (From *The Mansions of England in Olden Time*, by Joseph Nash, Henry Sotheran & Co., 1971.)

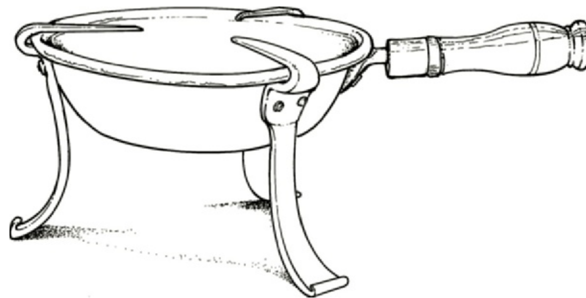


Figure 16.2b A portable charcoal brazier was used for heating and cooking in warm climates by the upper classes.

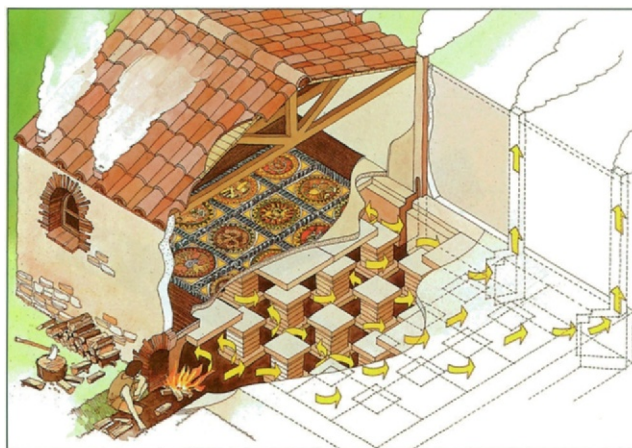


Figure 16.2c Roman hypocaust heating. Only about 10 percent of the fuel's energy ends up as heat in the space. (Courtesy of Wirsbo Company.)

Although buildings were now relatively smoke-free, heating them became much harder because the efficiency of fireplaces is very low. The fireplace remained popular in England because of the relatively mild climate (Fig. 16.2e), but in colder parts of Europe, the ceramic stove, with its much higher efficiency (between 30 and 40 percent), became popular (Fig. 16.2f).

English settlers brought the fireplace to the New World, where the endless forests could feed the huge appetite of inefficient fireplaces in cold climates. Around big cities like colonial Philadelphia, the forests were soon cut down, and an energy crisis developed. Benjamin Franklin responded by inventing a more fuel-efficient cast-iron stove.

Franklin realized that the traditional fireplace has several serious deficiencies: it heats only by direct radiation, the hot gases carry most of the heat out through the chimney, and cold air is sucked into the building to replace the warmed room air pulled into the fire to support combustion. Franklin's design addressed two of these issues, but a good modern fireplace must address all three. Today, metal fireplace inserts enable room air to circulate around the firebox (Fig. 16.2g). Sometimes a fan is used to increase the heat transfer from the firebox to the room air. A special duct brings outdoor-combustion air to the fireplace. Thus, heated room air is not required to feed the fire. Doors are necessary to prevent any room air from being pulled into the fireplace. Otherwise, even when the fire has died out, the stack effect will continue to pull heated room air out through the chimney. But even with these features, modern fireplaces are still only about 30 percent efficient, while a modern metal stove can have an efficiency as high as 70 percent.

Central heating became quite popular in larger buildings in the nineteenth century. Gravity air and water systems



Figure 16.2d In traditional Korean homes, the kitchen floor was lower than other floors in the house, allowing smoke from the cooking fire to pass through the crawl space beneath the rest of the home, creating radiant floor heating.



Figure 16.2f In northern, central, and eastern Europe, masonry and ceramic stoves were used instead of the inefficient fireplace. Cast-iron and steel stoves are even more efficient because they conduct heat faster through the walls; however, the heavy masonry stoves stored heat for all-night warmth. In very cold climates like that of Russia, people lived and slept on top of very large masonry stoves.



Figure 16.2e In England, fireplaces remained popular because of the relatively mild climate. In colder climates, the ceramic stove was preferred. (From *The Mansions of England in Olden Time*, by Joseph Nash, Henry Sotheran & Co., 1971.)

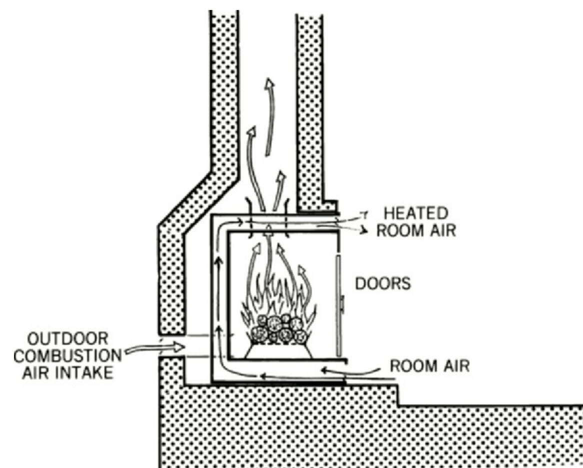


Figure 16.2g A modern, efficient fireplace must have doors, outdoor-combustion air intake, and a firebox around which room air can circulate.

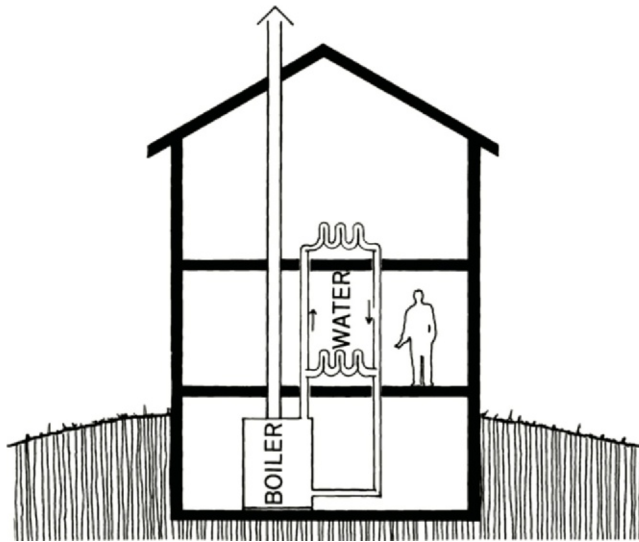


Figure 16.2h The first modern central heating system, which first appeared in the nineteenth century, used gravity hot-air or gravity hot-water systems. Large ducts or pipes allowed natural convection currents to transfer the heat from the basement to the rest of the house.

worked especially well in multistory buildings with basements. The furnace or boiler, located in the basement next to the wood or coal bin, heated the air or water to create strong natural-convection currents (Fig. 16.2h). By adding pumps and fans, modern heating systems have become more flexible and respond faster.

When choosing or designing a heating or cooling system for a building, one must first know how many different thermal zones are required.

16.3 THERMAL ZONES

Because not all parts of a building have the same heating or cooling demands, mechanical systems are designed to provide separate environmental control to building areas called **zones**. Each zone has a separate thermostat to control the temperature, and sometimes a humidistat to control the moisture content of the air. One reason for separate zones is the difference in exposure. A north-facing space might require heating, while a south-facing space in the same building requires cooling. A west-facing room might require heating in the morning and cooling in the afternoon. Since interior spaces have only heat gains, they require heat removal all year. Thus, a large office building would be divided into at least five zones on the basis of exposure (Fig. 16.3).

Frequently, additional zones are required because of differences in scheduling and occupancy. For example, a large conference room requires separate thermal control; otherwise, it will be too cold when only a few people are present and too hot when the room is full. Also, buildings are often zoned on the basis of rental areas. The number of zones required is an important factor in choosing a particular mechanical system.

16.4 HEATING SYSTEMS

Two additional considerations in choosing a heating system are the source of energy (fuel) used and the method of distribution within the building. The choice of a fuel usually depends on both economic factors and what is available. The main choices are gas, oil, coal, electricity, solar energy, and the use of waste heat. Except in rural areas, wood is usually too polluting and expensive to be a practical fuel. In some areas, wood waste is shredded and compressed into pellets that can be automatically fed into high-efficiency, low-polluting burners.

Oil, coal, wood, bottled gas, and active solar energy require building storage space (Fig. 16.4a). Electricity is popular because of its great convenience. Solar energy, the only renewable source in the list, was discussed

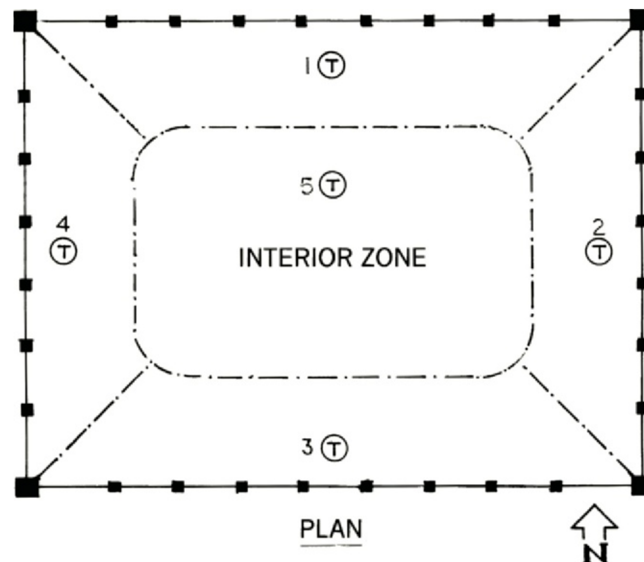


Figure 16.3 A large office building would require at least five zones based on differences in exposure. Each zone will have its own thermostat.

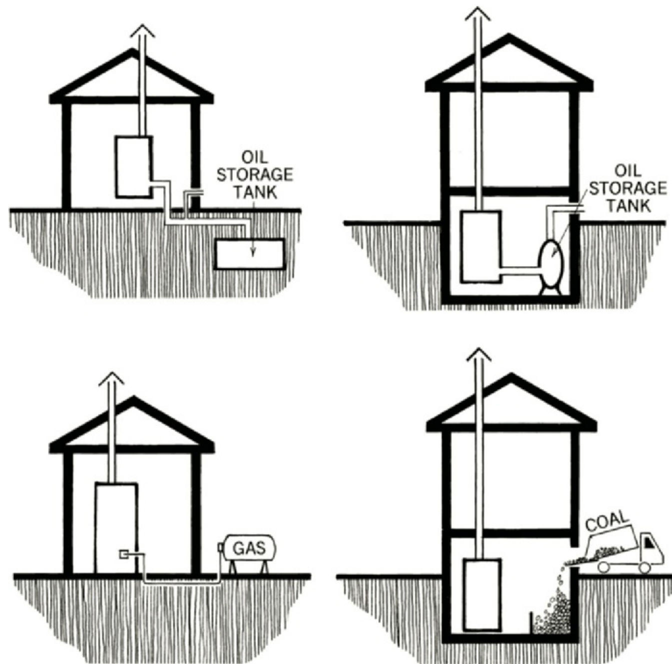


Figure 16.4a Oil, coal, wood, bottled gas, and active solar energy require a significant amount of storage space.

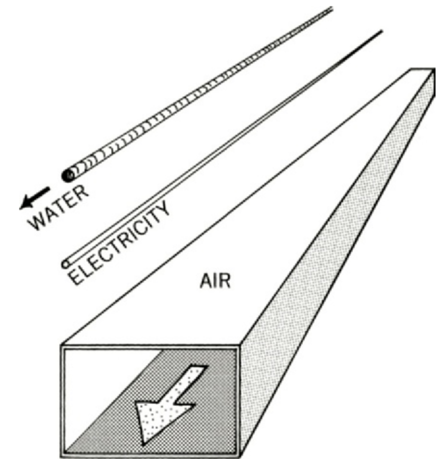


Figure 16.4b An air system requires a substantial amount of a building's volume for ducts and air-handling equipment (1–5 percent), while water and electrical systems require far less.

in Chapters 7 and 8. Waste heat from a combined heat and power (CHP) system was explained in Section 3.21.

Since the distribution system has a great effect on the architecture, one must select it with care. Heat can be distributed in a building by air, water, or electricity. Because of their large size, air ducts require the most forethought, while electric wires require the least (Fig. 16.4b). The space required for ducts and air-handling equipment varies between 1 and 5 percent of the total volume of a building. It also takes twenty times more energy to move heat by air with fans than water by pumps. The advantages and disadvantages of air, water, and electric distribution systems are summarized in Table 16.4.

Table 16.4 Heating Distribution Systems

System	Advantage	Disadvantage
Air	Can also perform other functions, such as ventilation, cooling, humidity control, and filtering. Prevents stratification and uneven temperatures by mixing air. Very quick response to changes of temperature. No equipment required in rooms being heated.	Very bulky ducts require careful planning and space allocation. Can be noisy if not designed properly. Very difficult to use in renovations of old buildings. Zones are not easy to create especially in small buildings. It takes much more energy to move heat with air than with water.
Water	Compact pipes are easily hidden within walls and floors. Can be combined with domestic hot water system. Good for radiant floor heating. Easy zoning. Very quiet.	For the most part, can only heat and not cool (exceptions: fan-coil units and radiant ceiling panels) No ventilation. No humidity control. No filtering of air. Leaks can be a problem. Slightly bulky equipment in spaces being heated if baseboard and cabinet convectors are used. Radiant floors are slow to respond to temperature changes.
Electricity	Most compact. Quick response to temperature changes. Very easily zoned. Low initial cost. Good for spot heating. Very quiet if there is no fan.	Very expensive to operate (except heat pump). Not sustainable because of low source energy efficiency.

16.5 ELECTRIC HEATING

Although many different types of electric-heating devices exist, most use resistance-heating elements to convert electricity directly into heat. The exceptions are the heat pump and heat from the lighting system.

Figure 16.5a illustrates the general types of resistance-heating devices that are available for heating a room. A great advantage of all the devices shown is that they allow many heating zones to be easily established—each room or part thereof can be a separate zone. Electric boilers or furnaces to heat central hot-water or air systems do not have this advantage. Since electric resistance heating is expensive to operate and is not sustainable, it should be used only in mild climates or for spot-heating small areas.

The baseboard units heat by natural convection, while the unit heaters have fans for forced convection. Radiant heating is possible at three different intensities. Because of their large areas, radiant floors and ceilings can operate at rather low temperatures (80° and 110°F [25° and 45°C], respectively). Radiant panels on walls or ceilings must be hotter (about 190°F [85°C]) to compensate for their smaller areas. They are used to increase the mean radiant temperature (MRT) near large areas of glazing or other cold spots. High intensity infrared lamps operate at over 1000°F (550°C) and, therefore, can be quite small. They look similar to fluorescent fixtures except that the linear quartz lamps glow red hot. These high intensity infrared heaters are designed not to heat air but rather solid objects, such as walls, furniture, and people. Therefore, these heaters can be used outdoors for purposes like keeping people warm in front of hotel or theater entrances. They are often used for outdoor seating areas of restaurants to extend the hours of use. They are also appropriate in buildings such as warehouses or aircraft hangars, where it is impractical to heat the air. High intensity infrared heaters can also be powered by gas instead of electricity.

With the above-mentioned resistance-heating devices, one unit of energy in the form of electricity is turned into one unit of heat—a poor choice because high-grade energy is thereby degraded into an equivalent amount of low-grade energy. However, with a heat pump, about three units of heat energy can be created for every unit of electrical energy used. The secret of this apparent "free lunch" is that the electricity is not converted into heat, but is used instead to pump heat from outdoors to indoors. Heat is extracted from the cold outdoor air and added to the warm indoor air. Thus, in effect, the heat is pumped "uphill," which is what all refrigeration machines do. A heat pump is a special kind of air conditioner running in reverse during the winter.

Heat pumps are appropriate where both summer cooling and winter heating are required. Since the efficiency of heat pumps drops with the outside temperature, they are not appropriate in very cold climates. The efficiency of heat pumps is described by the **coefficient of performance (COP)**, which is defined as

$$\text{COP} = \frac{\text{energy out}}{\text{energy in}}$$

In mild climates, a COP as high as 4 can be achieved, while in cold climates it will be under 2. Much better efficiencies are possible by coupling the heat pump with the ground rather than the outdoor air, because the ground is much warmer in the winter and cooler in the summer. Ground-coupled heat-pump systems will be explained after heat pumps are explained in Section 16.10.

Although lights are always a source of heat, they are no more efficient than resistance heating elements (COP = 1). There is a system, however, in which the lighting can be efficiently used for heating. In a large office building, a sizable interior zone requires cooling even in the winter (Fig. 16.3). If the warm return air from the core is further heated by being returned through the lighting fixtures, it will be warm enough to heat the perimeter area of the building (Fig. 16.5b). A side benefit of this

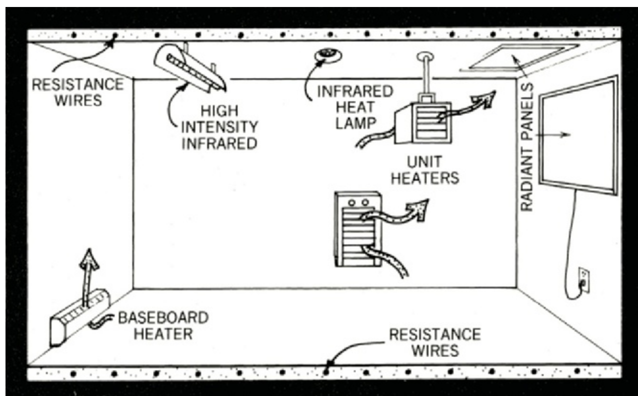


Figure 16.5a The various types of electric resistance heaters located within a room are shown.

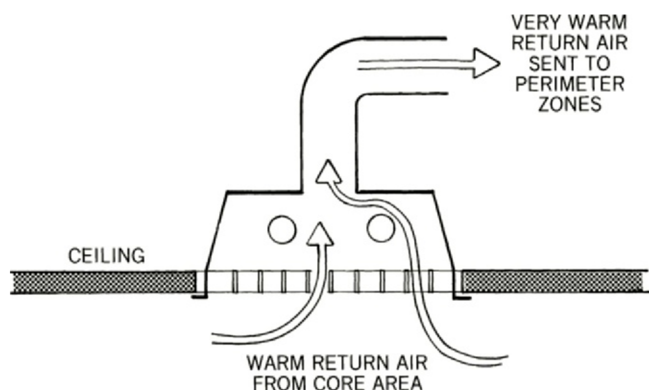


Figure 16.5b Air is heated by returning it through the lighting fixtures. The heated air can then be used to heat the perimeter areas of a building.

system is that the lamps and fixtures last longer because they are cooled by the return air.

16.6 HOT-WATER (HYDRONIC) HEATING

Any of the fuels mentioned before can be used to heat water in a boiler (Fig. 16.6a). The hot water can distribute the heat throughout the building in several ways.

One of the most comfortable hydronic heating systems is similar to the Roman hypocaust. Instead of fire, hot water is pumped through coils of plastic tubing embedded in the floor (Figs. 16.6b–d). When concrete slabs are used, the coils can be cast right into the slab. Fortunately, many systems have also been developed for using radiant heating with wooden floors.

A radiant floor will heat the space by both radiation and natural convection. Radiant floors are very comfortable because we enjoy having warm feet and cool heads. For the same reason, radiant ceilings are not very comfortable: they give us a warm head and cool feet. Because the coils are usually embedded in thermal mass

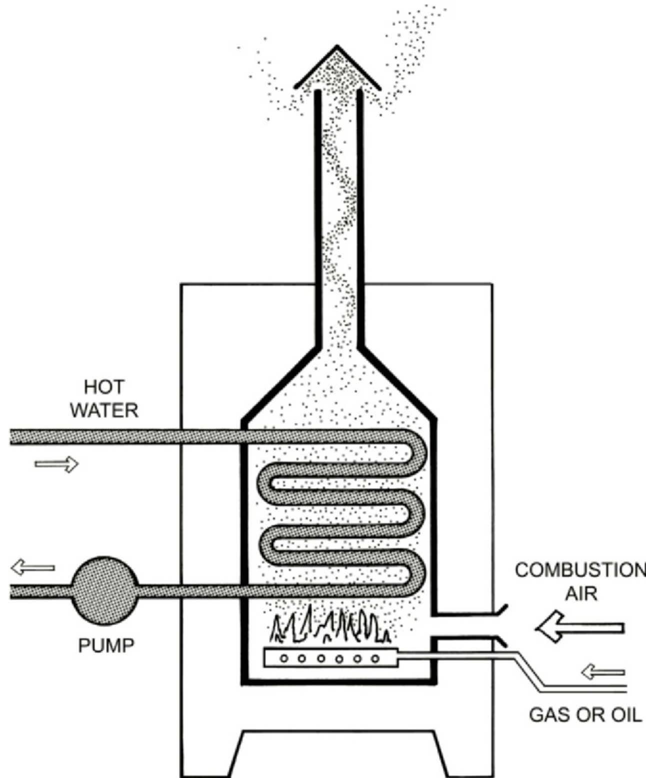


Figure 16.6a A conceptual section of a boiler for a hot-water (hydronic) heating system is shown. Wood pellets can also be used.



Figure 16.6c For slab-on-grade radiant-floor heating, the concrete is poured over the plastic tubing. The various heating zones are made with continuous tubing, with all joints made above the slab to minimize leaks in the concrete.

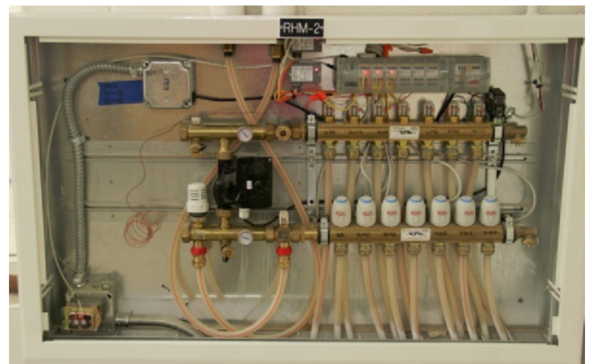


Figure 16.6d The manifold for distributing hot water to a radiant floor system is located behind a panel for easy adjustments and repairs.

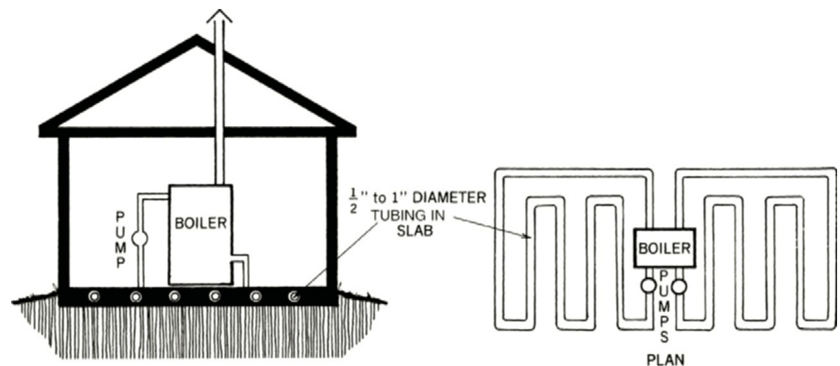


Figure 16.6b Radiant-floor hot-water heating systems are excellent for cold climates. Each loop can be a separate zone.

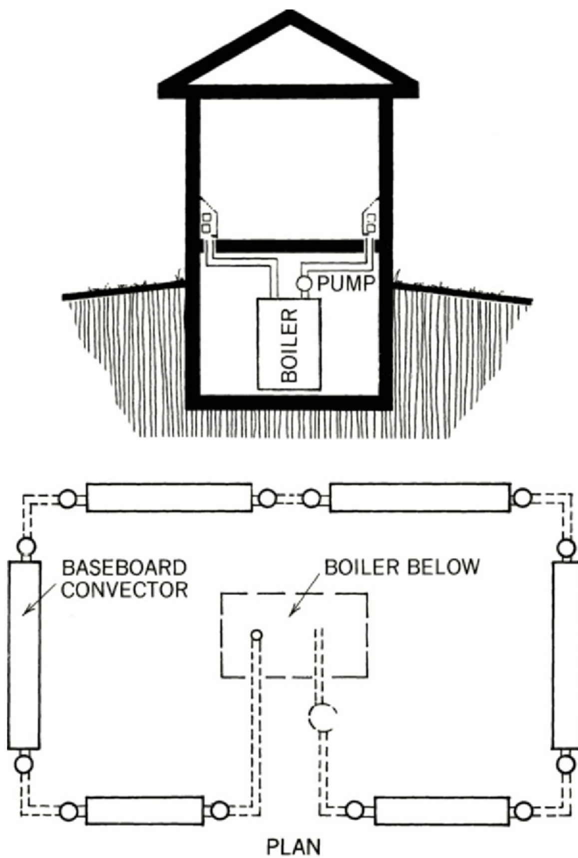


Figure 16.6e A hot-water system with baseboard convectors is shown.

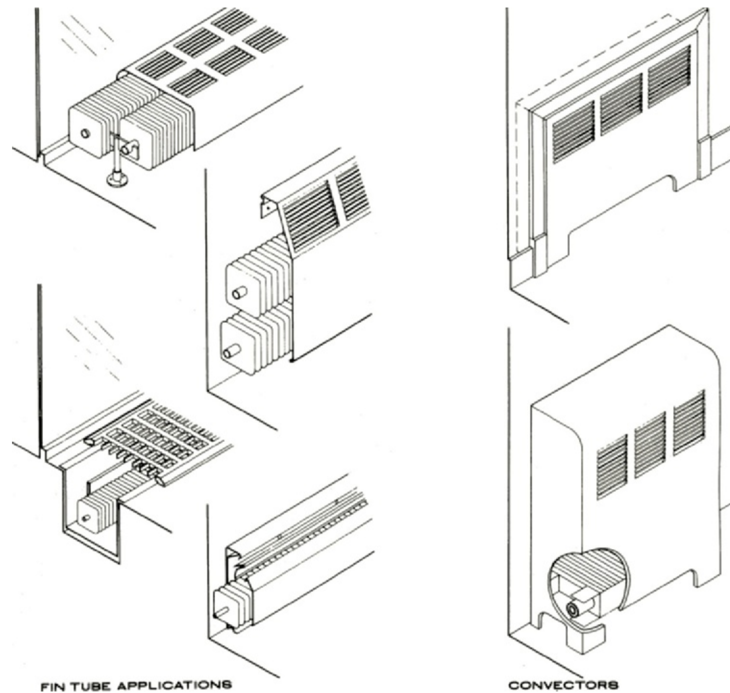


Figure 16.6g Baseboard convectors are unobtrusive but can be blocked by furniture. Cabinet convectors are usually placed under windows. Underfloor convectors are appropriate for areas with floor-to-ceiling glass. (From *Architectural Graphic Standards*, Ramsey/Sleeper, 8th ed., John R. Hoke, editor, © John Wiley & Sons, Inc., 1988.)

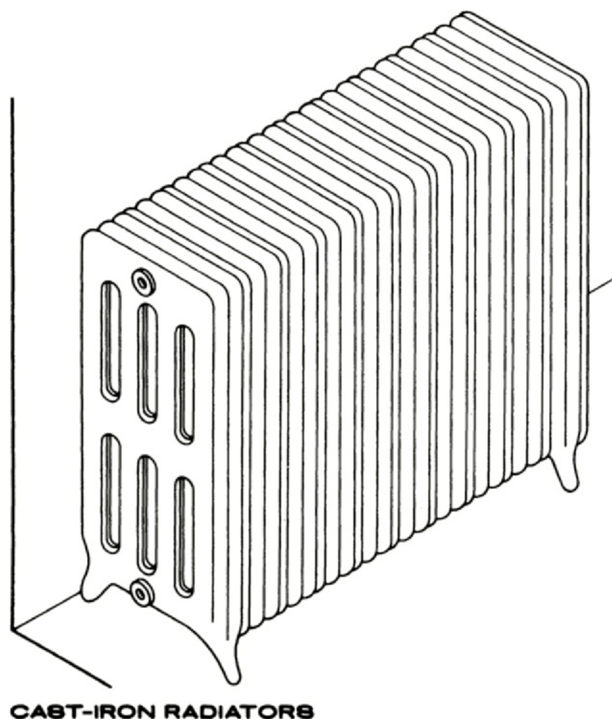


Figure 16.6f Cast-iron radiators heat primarily by convection. (From *Architectural Graphic Standards*, Ramsey/Sleeper, 8th ed., John R. Hoke, editor, © John Wiley & Sons, Inc., 1988.)

or under a wooden floor, there is a long time lag in receiving heat after the system is turned on. The time lag is an advantage in climates and buildings in which the heating demand is fairly constant, but this time lag is a disadvantage when the heating load is intermittent and the system must respond quickly.

Radiant floor heating is a good match for active solar because solar collectors can efficiently produce the relatively low water temperatures needed (about 90°F [32°C]) (see Chapter 8).

Most hot-water systems use convectors to transfer the heat from the water to the air of each room (Fig. 16.6e). In the past, hot-water systems used cast-iron radiators, which, in fact, heated mostly by convection (Fig. 16.6f). Today, most convectors consist of fin-tubes or fin-coils to maximize the heat transfer by natural convection (Fig. 16.6g). Baseboard



Figure 16.6h These sculptural, elegant convector/radiators are designed to be exposed to view. (Courtesy of 3-D Laboratory, Inc.)

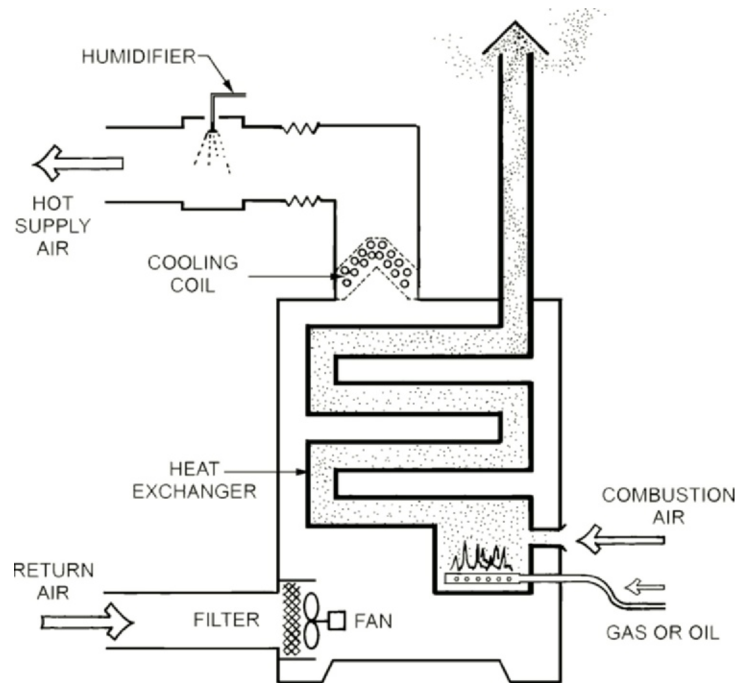


Figure 16.7a A conceptual section of a hot-air furnace with optional cooling coils and humidifier is shown.

convectors are linear units placed parallel to exterior walls, while cabinet convectors concentrate the heating where it is most needed—under windows to counteract the cold downdraft and low MRT of the windows. When there is a large area of glazing from floor to ceiling, a below-floor convector can be used.

Most convectors are designed to be as unobtrusive as possible because it is assumed that mechanical equipment must be ugly. Some architects and manufacturers take a different approach, as can be seen in the elegant radiator/convectors in Figure 16.6h.

Because convectors rely on natural convection, they must be placed low in a room. However, if a fan is used for forced convection, any mounting position is possible. Because such fan-coil units can also be used for cooling, they are discussed under cooling systems.

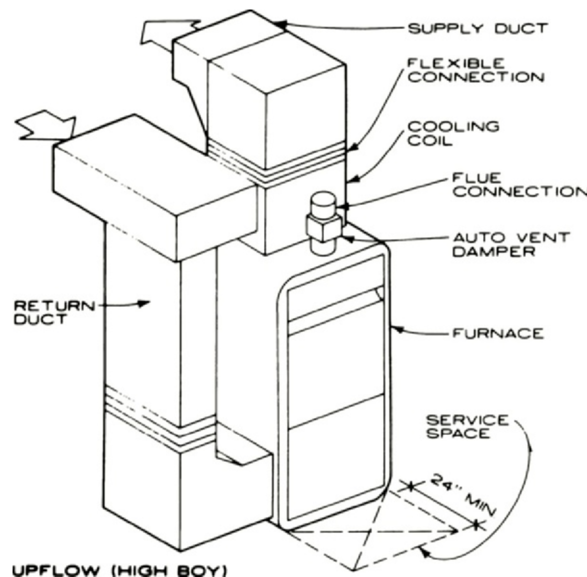


Figure 16.7b An isometric of a hot-air furnace with a cooling coil is shown. (From *Architectural Graphic Standards*, Ramsey/Sleeper, 8th ed., John R. Hoke, editor, © John Wiley & Sons, Inc., 1988.)

16.7 HOT-AIR SYSTEMS

Air systems are popular because they can perform the whole range of air-conditioning functions: heating, cooling, humidification, dehumidification, filtering, ventilation, and air movement to eliminate stagnant and stratified air layers. Hot-air heating systems are especially popular where summer cooling is also required. Those hot-air systems that supply air at or near floor level around the perimeter of the building are most suitable for cold climates, where the heating season is the main consideration. These systems are discussed here, while those more suitable for hot climates will be discussed along with other cooling systems.

A hot-air furnace uses a heat exchanger to prevent combustion air from mixing with room air. A blower and filter are standard, while a humidifier and cooling coil are optional (Figs. 16.7a and 16.7b). Gas furnaces can be very efficient. Some pulse-type gas furnaces convert more

than 95 percent of the gas energy into useful heat.

For slab-on-grade construction in cold climates, the loop-perimeter system offers the greatest thermal comfort (Fig. 16.7c). The supply air heats the slab where it is coldest—at the edge. Thus, this system offers the benefits of both hot-air and radiant-slab heating. The main disadvantage is the high initial cost of the system.

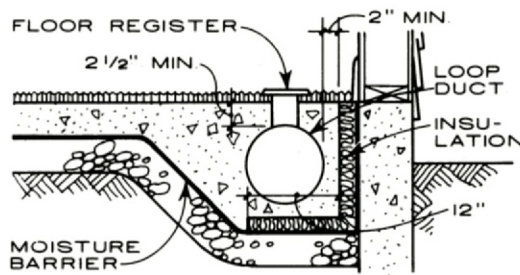
The **radial-perimeter system** is more suitable for crawl space or attic construction (Fig. 16.7d). If the crawl space is high enough (about 4 ft [1.2 m]), a special horizontal furnace can be used (Fig. 16.7e). The same horizontal furnaces are sometimes also used in attic spaces. The author has crawled through spaces so tight that it was a puzzle how the equipment and ducts were ever installed. Of course, the craftsmanship was very poor and the ductwork was very leaky, which is not just inefficient but also unhealthy, as will be explained later. Thus, the architect's design must also consider installation and servicing. By far the best solution, however, is to keep the ducts and equipment within the thermal envelope.

Ductwork should always be on the indoor side of the thermal envelope!

The **extended-plenum system** is appropriate for buildings because it enables the supply ducts to run parallel and between the joists, thereby saving much space and headroom (Figs. 16.7f and 16.7g).

For heating single spaces, a **wall furnace** can be a practical solution because no ductwork is required. When powered by gas, these wall furnaces can draw combustion air and vent directly through the wall on which they are attached (Fig. 16.7h).

In spaces with high ceilings, unit heaters powered by gas, electricity, or hot water are often appropriate because they take up no floor area (Fig. 16.7i).



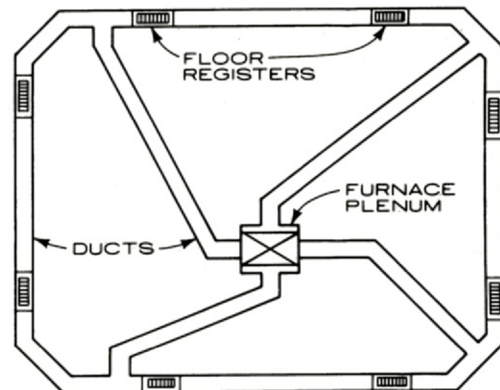
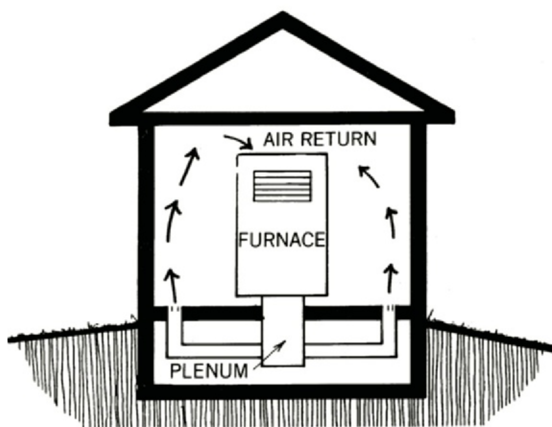


Figure 16.7c A loop-perimeter system for slab-on-grade construction is most appropriate for cold climates. (From *Architectural Graphic Standards*, Ramsey/Sleeper, 8th ed., John R. Hoke, editor, © John Wiley & Sons, Inc., 1988.)



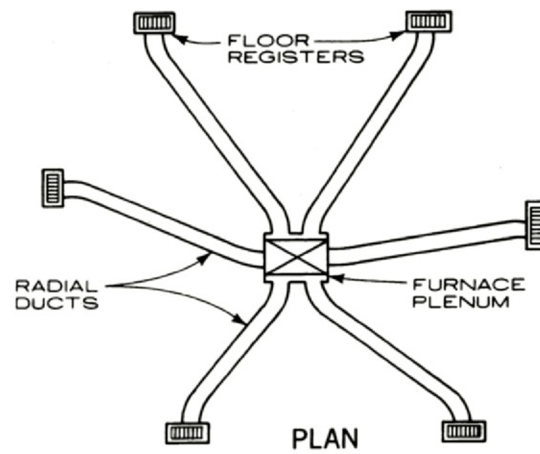
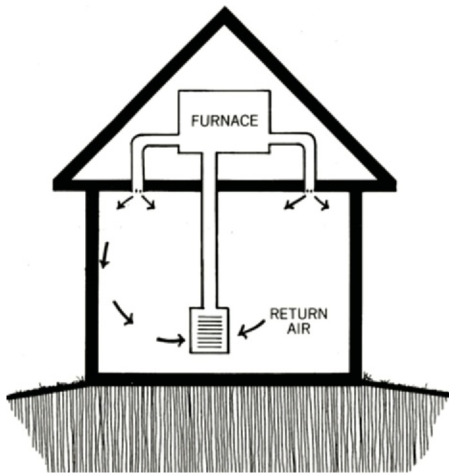


Figure 16.7d A radial-perimeter system is shown for crawl space construction but is more appropriate for use in the attic. (From *Architectural Graphic Standards*, Ramsey/Sleeper, 8th ed., John R. Hoke, editor, © John Wiley & Sons, Inc., 1988.)



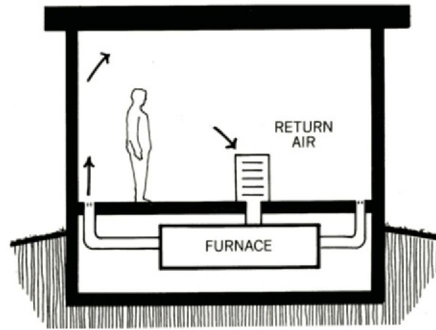
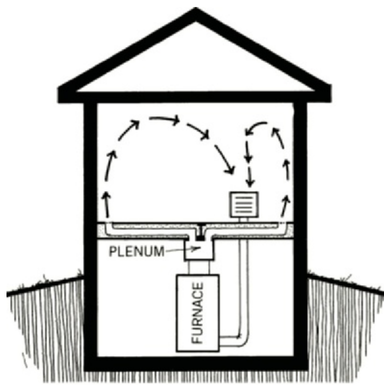


Figure 16.7e Although horizontal furnaces are available for use in crawl spaces or attics, it is much better to have all ducts and equipment within the thermal envelope for both health and efficiency reasons.



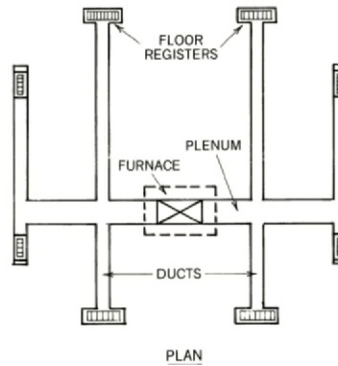
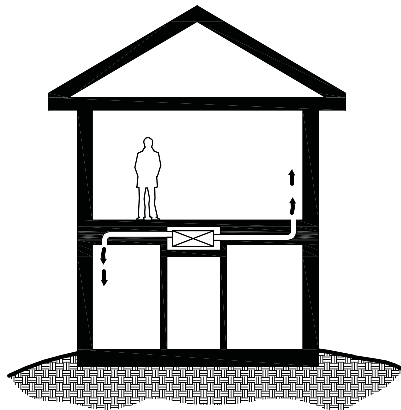


Figure 16.7f The extended-plenum system for basement construction has the supply ducts run parallel and between joists to save on headroom.



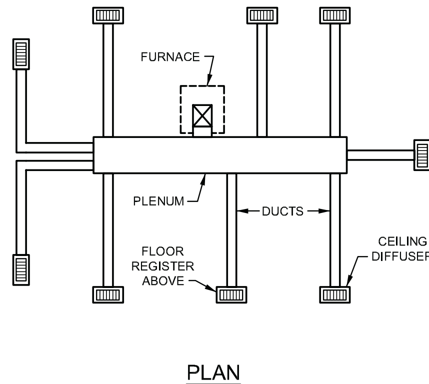
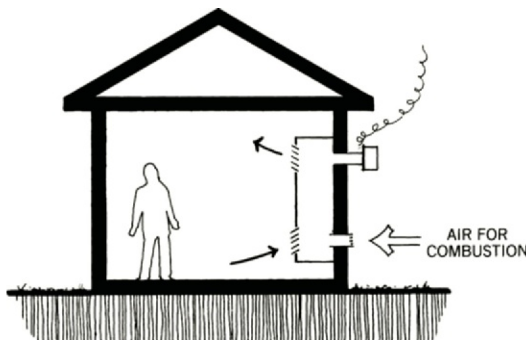


Figure 16.7g The extended plenum above the corridor ceiling system provides both health and energy efficiency benefits.



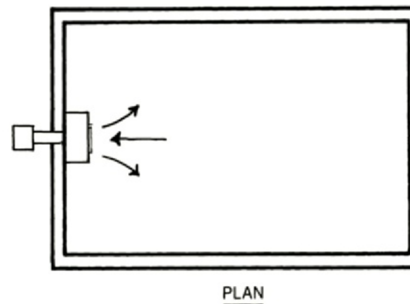


Figure 16.7h Wall furnaces can be appropriate for heating single spaces.

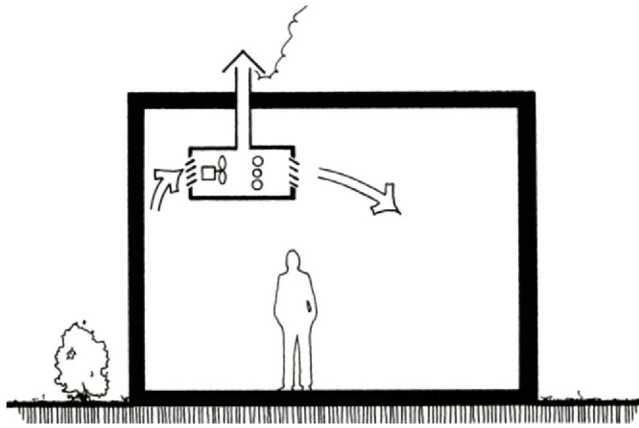


Figure 16.7i Unit heaters can be appropriate for spaces with high ceilings. A fan forces the hot air down. The heat source can be electricity, hot water, or gas. If gas is used, the heater must be vented.

16.8 COOLING

Cooling is not as intuitively clear and simple as heating. Cooling, the removal of heat, can be better understood by means of a water analogy. A building in the summer is surrounded by heat trying to get in, just as water tries to get into a submerged building (Fig. 16.8a). The water in the analogy is gained both through the envelope and from internal sources. The natural tendency is for the water to flow into the building. Only by pumping it uphill can it be removed again.

In the same way, the natural tendency is for heat to flow inward when the outdoor temperature is higher than the indoor temperature. The only way to remove the heat is with a machine that pumps heat from a lower temperature to a higher temperature. Such a device is called a refrigeration machine (Fig. 16.8b). Before the invention of refrigeration machines about 150 years ago, there was no way to actively cool a building. Although blocks of ice harvested in winter could cool a building, the huge amount of ice required made that impractical on all but the smallest scales. One of the big trade items in the nineteenth century was ice, which was harvested from New England lakes in the winter and shipped to the South in the summer. Because of ice's high cost, it was primarily used for cooling food and drinks.

Until the late nineteenth century, the only way to achieve some summer comfort was to use the heat-rejection and passive-cooling techniques mentioned previously. Shading, natural ventilation, evaporative cooling, and thermal mass were the main techniques used.

In the 1840s, Dr. John Gorrie, a physician in Apalachicola, Florida, built the first refrigeration machine in an attempt to help his patients who were suffering from malaria. Although his machine worked, refrigeration was not used to cool buildings until the 1920s, when a new type of building had a special need for air-conditioning. Because movie houses had to close their windows to keep the light out, they also kept the cooling breezes out. So, most people had their first experience with air-conditioning at movie houses, where the marquees announced "air-conditioned" in larger letters than the titles of the movies. Although air-conditioning was still considered

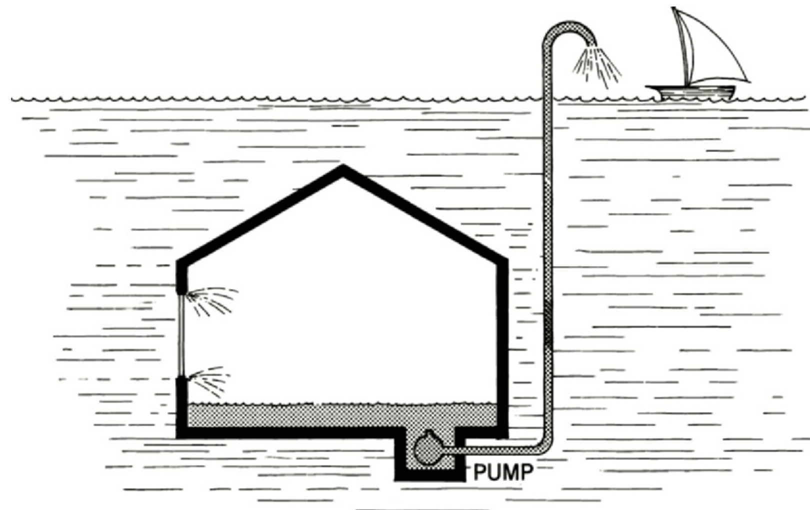


Figure 16.8a In the water analogy for cooling, any water that finds its way into the submerged building must be pumped "uphill" to get it out.

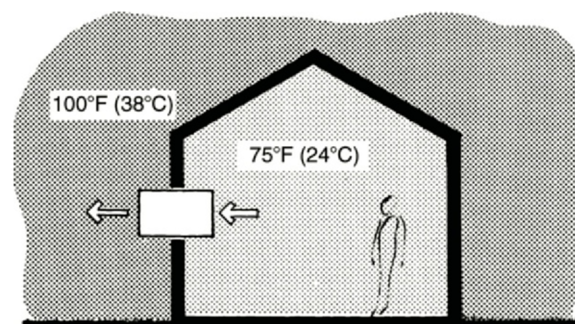


Figure 16.8b A refrigeration machine pumps heat from a lower to a higher temperature (e.g., 75° to 100°F) (24° to 38°C).

a luxury in the United States in the 1950s, it is now considered a necessity almost everywhere on the planet.

16.9 REFRIGERATION CYCLES

The refrigeration machine, which pumps heat, is the critical element of any cooling system. There are basically three refrigeration methods: vapor compression, absorption, and thermoelectric. The compression cycle is the most common, but the absorption cycle is often appropriate when a source of low-cost heat is available. The thermoelectric cycle, which turns electricity directly into heating and cooling effects, is not used for buildings.

The Vapor Compression Refrigeration Cycle

The **vapor compression refrigeration cycle** depends on two physical properties of matter:

1. A large amount of **heat of vaporization** is required to change a liquid into a gas. Of course, this heat is released again when the gas condenses back into a liquid.
2. The boiling/condensation temperature of any material is a function of pressure. For example, 212°F (100°C) is the boiling point of water only at the pressure of sea level (14.7 lb/in.^{2}) (101 kPa). When the pressure is reduced, the boiling point is also reduced.

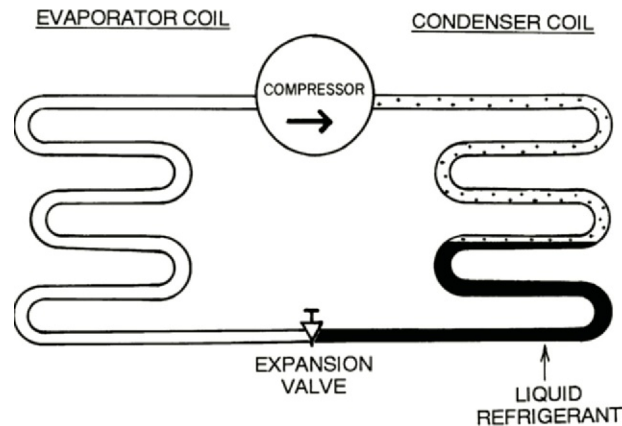


Figure 16.9a The basic components of a compressive refrigeration machine are shown.

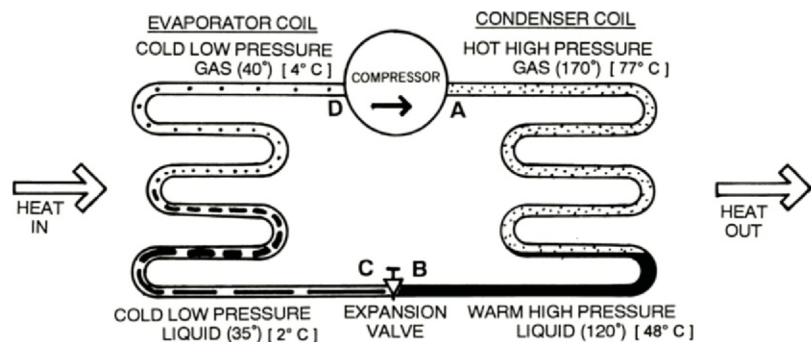


Figure 16.9b Where the refrigerant evaporates, it absorbs heat (cools), and where it condenses, it gives off heat.

The basic elements of a compression refrigeration machine are shown in Figure 16.9a. Imagine that the valve is closed and the compressor has pumped most of the refrigerant into the condenser coil. When the valve is slightly opened, only a small stream of liquid refrigerant can enter the partial vacuum of the evaporator coil at point C in Figure 16.9b. The refrigerant boils (evaporates) because of the very low pressure. To change state, the liquid will require the large amount of heat called heat of vaporization. Thus, the evaporator coil will cool as it gives up its sensible heat to allow the liquid refrigerant to change into a gas (i.e., boil).

To keep the process going, the compressor continues to pump the refrigerant gas back into the condenser coil. A high-pressure gas collects at point A. Since any gas under pressure heats up, the condenser coil gets hot. As the coil loses heat, the high-pressure refrigerant gas will be able to condense and give up its heat of vaporization. Thus, a warm, high-pressure liquid will collect at point B. The cycle now repeats as a small amount of liquid refrigerant enters the evaporation coil at point C and evaporates to collect as a low-pressure gas at point D.

Almost all refrigerants were made of chlorofluorocarbons (CFCs) until 1987, when the world agreed through the Montreal Protocol to phase out these ozone-damaging compounds.

New refrigerants made of **hydrofluorocarbons (HFCs)** are 90 percent less damaging to the ozone but are still significant greenhouse gases when they escape from refrigeration machines. Other possible refrigerants include ammonia, propane, and isobutane, but these are all flammable, and ammonia is also toxic.

In the vapor compression cycle, power is required to drive refrigerant pumps that are of the reciprocating, scroll/screw, or centrifugal types. The reciprocating compressor is most appropriate for small to medium-sized buildings, while the centrifugal compressor is best for medium-sized to large buildings. When any of these refrigeration machines are used to chill water, they are known as chillers.

The Absorption Refrigeration Cycle

The **absorption refrigeration** cycle depends on the same two properties of matter described above for the compressive cycle, as well as a third property:

3. Some liquids have a strong tendency to absorb certain vapors. For example, water vapor is absorbed by liquid lithium bromide or ammonia. These materials are also known as desiccants.

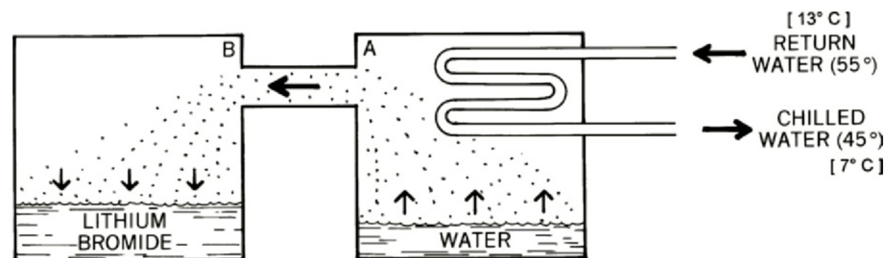


Figure 16.9c The first two chambers of an absorption refrigeration machine are shown.

The absorption refrigeration machine requires no pumps or other moving parts, but it does require a source of heat, such as a gas flame or the waste heat from an industrial process. The machine consists of four interconnected chambers, of which the first two are shown in Figure 16.9c.

In chamber A, water evaporates and in the process draws heat from the chilled water coil (output). The water vapor migrates to chamber B, where it is absorbed by the lithium bromide. Consequently, the vapor pressure is reduced, and more water can evaporate to continue the cooling process. Eventually, the lithium bromide will become too dilute to further absorb water. However, some of the lithium bromide flows into chamber C of Figure 16.9d, where an external heat source boils the water off the lithium bromide. The concentrated lithium bromide is then returned to chamber B, while the water vapor is condensed back into water in chamber D. The last step is to return the liquid water back to chamber A so that the cycle can continue.

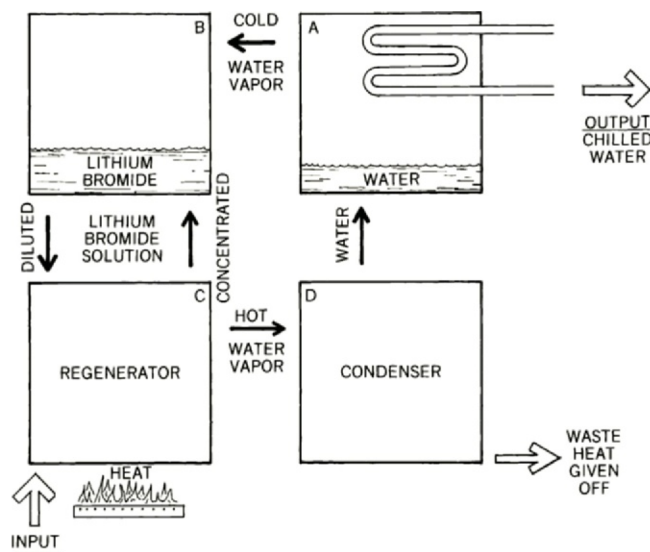


Figure 16.9d The absorption refrigeration cycle has chilled water as an output and a heat source as an input. Waste heat is given off in the process.

Because the absorption refrigeration cycle is inherently inefficient, the cycle is economical only when an inexpensive source of heat is available. Solar-heated water may become such a source of heat when collectors are mass-produced and electricity becomes more expensive. Although the vapor compression cycle is more efficient, it requires a source of mechanical power, which is supplied by an electric motor running on valuable electricity.

Recently, a hybrid air-conditioning cycle was introduced. The Advantix system uses a compressor to cool the air and a desiccant to dehumidify it.

Sometimes **evaporative coolers** are included in a discussion of refrigeration machines. Although evaporative coolers often replace air conditioners in dry climates, most types do not remove total heat from a building. Instead, they convert sensible heat into latent heat, which in dry climates creates thermal comfort very economically. Because of their mechanical simplicity, they were discussed with other passive cooling systems in Section 10.12.

16.10 HEAT PUMPS

Every compressive refrigeration machine pumps heat from the evaporator coil to the condenser coil. Figure 16.10a illustrates a simple through-the-wall or window air-conditioner unit that is essentially a refrigeration machine. One fan cools indoor air by blowing it across the cold evaporator coil, while another fan heats outdoor air by blowing it across the condenser coil.

What would happen if the air-conditioning unit were turned around so that the evaporator coil were outdoors and the condenser coil were indoors? The outdoor air would then be cooled, and the indoor air would

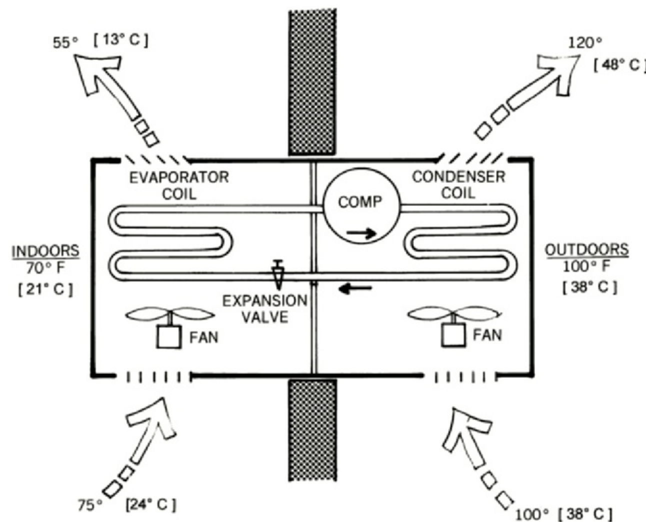


Figure 16.10a A simple through-the-wall air-conditioner unit essentially consists of a vapor compression refrigeration machine.

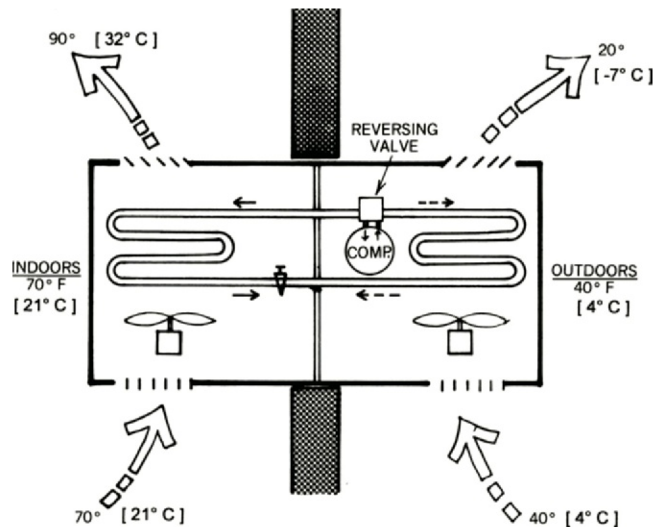


Figure 16.10b In a heat pump, the reversing valve allows the refrigerant to flow in either direction. In the winter condition shown, the outdoor coil becomes the evaporator and the indoor coil the condenser. An air-to-air heat pump is shown. In a ground-coupled heat pump, water would transfer the heat between the outdoor coil and the ground.

be heated—just what is needed in the winter.

Instead of turning the whole unit around, it is much easier to just reverse the flow of refrigerant. That also makes it unnecessary to go outside in the winter to reach the controls. A refrigeration machine in which the flow of refrigerant can be reversed is called a heat pump. The term is unfortunate because every refrigeration machine pumps heat, even if it is only in one direction. Heat pumps use reversing valves to change the direction of refrigerant flow (Fig. 16.10b).

Heat pumps are air conditioners that can switch to heating in the winter. Since they extract heat from outdoor air, their efficiency drops as the outdoor air gets colder. Thus, heat pumps are most appropriate in those climates where summer cooling is required and where the winters are not too cold. Much of the United States fits into this category. Special cold-climate heat pumps have been developed.

When heat pumps are coupled with the ground instead of with outdoor air, they are called geo-exchange (geothermal) heat pumps.

16.11 GEO-EXCHANGE

According to the Environmental Protection Agency (EPA), **geo-exchange** heat pumps are in many cases the most energy-efficient, environmentally clean, and cost-effective active space-conditioning systems available.

Geo-exchange heat pumps are also known as **geothermal** or **ground-coupled** heat pumps. "Ground-coupled" is a good descriptive term, but "geothermal" is not because it is already in use to describe high-temperature heat obtained from deep within the earth. "Geo-exchange" is an excellent term, because in the summer, heat pumps move heat from indoors to the ground, which acts as a heat sink, and in the winter, the heat is moved back from the ground and pumped indoors again—a seasonal exchange with the earth ("geo").

Water is used to transfer the heat from the heat pump to and from the upper layer of the earth (less than 100 ft [30 m]). Four different methods are available, and the best choice depends on the local conditions. If a pond, lake, or river is available, it can be the most convenient heat source/heat sink (Fig. 16.11a). Where groundwater is plentiful and well drilling is easy, an open-loop system can be used; here, the water is pumped out of the ground at one well and returned at another well (Fig. 16.11b). A closed loop is usually preferred because much less pumping energy is required (Fig. 16.11c).

Vertical closed loops are preferred over horizontal closed loops because the deep ground is warmer

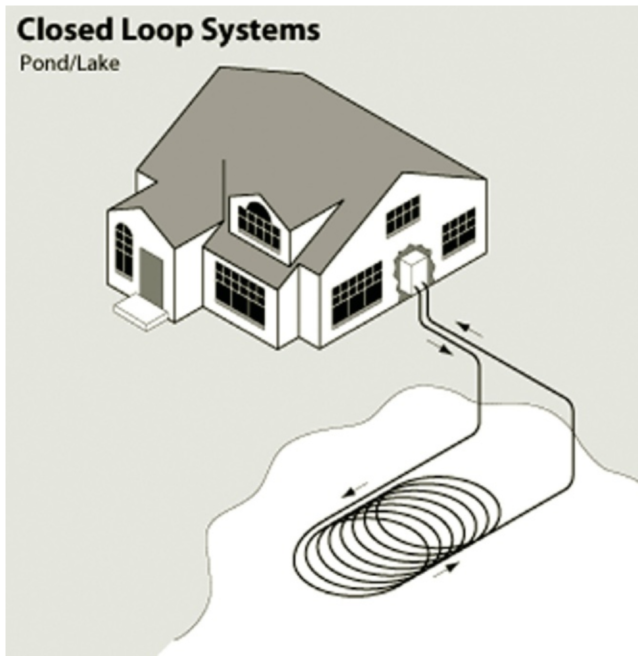


Figure 16.11a A geo-exchange heat-pump system can use a pond as the heat source/heat sink. (From U.S. Dept. of Energy, Office of Geothermal Technologies.)



Figure 16.11b A geo-exchange heat-pump system can use groundwater as the heat source/heat sink. The water should be returned to the ground via a second well. (From U.S. Dept. of Energy, Office of Geothermal Technologies.)

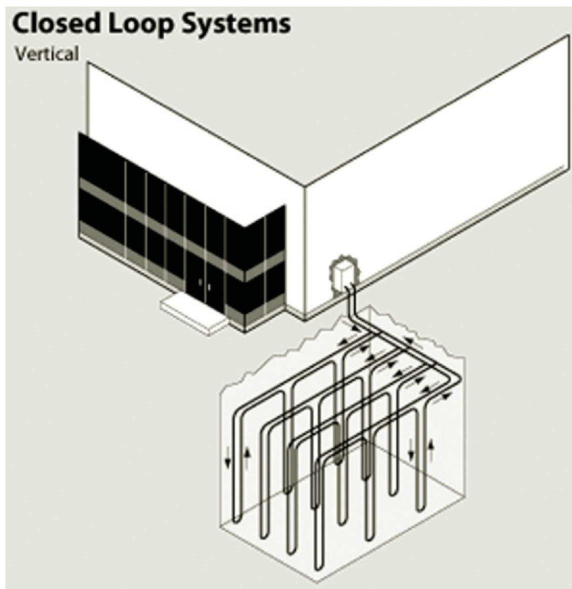


Figure 16.11c In many cases, vertical closed loops are the best option for geo-exchange heat pumps. (From U.S. Dept. of Energy, Office of Geothermal Technologies.)

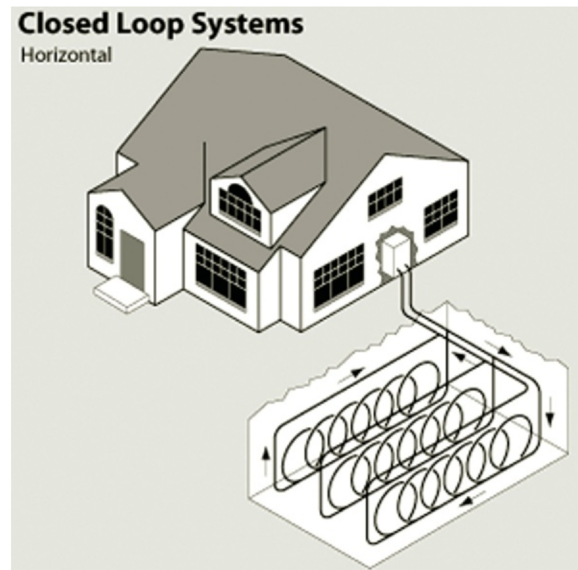


Figure 16.11d When soil conditions make vertical loops impractical and enough land is available, horizontal loops are acceptable. Trenches should be as deep as possible to obtain the best soil temperatures. (From U.S. Dept. of Energy, Office of Geothermal Technologies.)

in the winter and cooler in the summer than the shallow ground (see Section 10.14). Drilling deep holes can be expensive, however, especially if the ground is rocky. In such a case, if the site is large enough, horizontal loops in fairly deep trenches might be the most cost-effective alternative (Fig. 16.11d).

Since ground-coupled heat pumps are indoors, protected from the elements, they last much longer and require much less maintenance than conventional air conditioners. These pumps also have the aesthetic advantages of being hidden indoors and of making almost no noise. During the summer, the heat removed from

indoors can be first used to heat hot water, in effect yielding free domestic hot water. A device called a **desuperheater** is added to a standard heat pump to heat the hot water. The rest of the year, the domestic hot water is heated efficiently from the ground, like the rest of the building. The greatest benefit of geo-exchange heat pumps is their high efficiency. They use about 40 percent less energy than air-to-air heat pumps and about 70 percent less energy than standard air-conditioning with electric resistance heating. Because ground temperatures are less extreme than air temperatures, geo-exchange heat pumps are appropriate in most of the world where both heating and cooling are required.

16.12 COOLING SYSTEMS

To cool a building, a refrigeration machine must pump heat from the various rooms into a heat sink. The heat sink is usually the outdoor air but can also be a body of water or the ground (Fig. 16.12a). Cooling systems vary mostly by the way heat is transferred from the rooms to the refrigeration machine and from there to the heat sink (Fig. 16.12b). The choice of the heat-transfer methods depends on building type and size. Cooling systems are often classified by the fluids used to transfer the heat from the habitable spaces to the refrigeration machine. The four major categories are direct refrigerant, all-air, all-water, and combination air-water.

Direct Refrigerant Systems

The direct refrigerant or DX (direct expansion) system is the simplest, because it consists of little more than the basic refrigeration machine plus two fans. The indoor air is blown directly over the evaporator coil, and

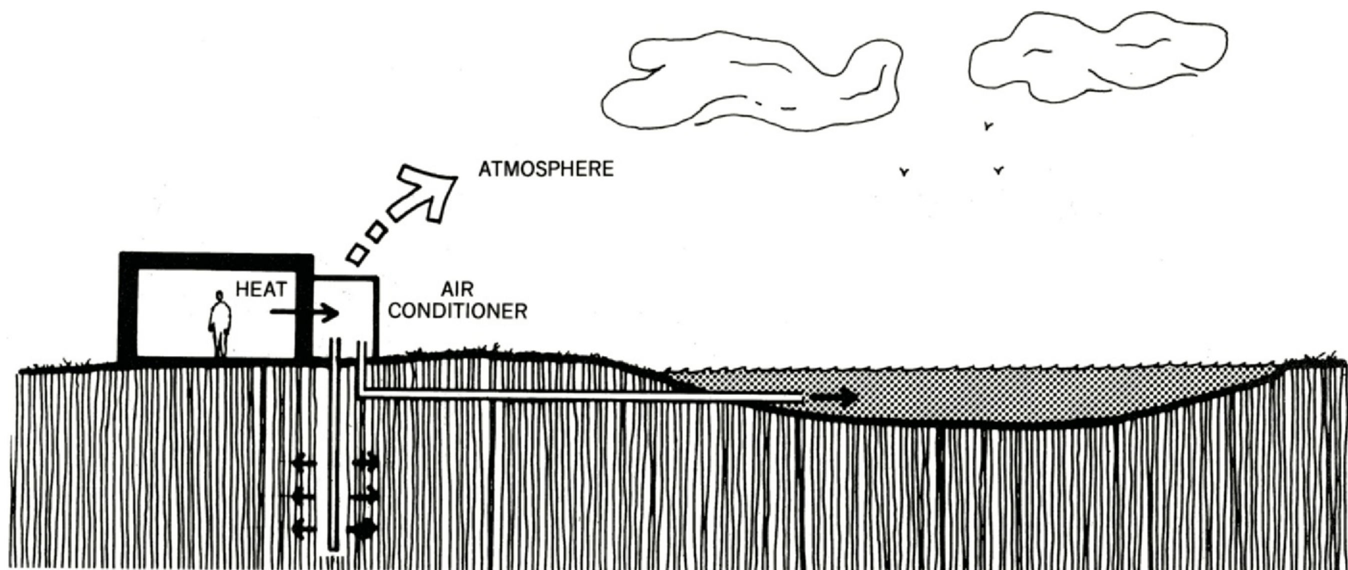


Figure 16.12a Air, water, or the ground can act as the heat sink for a building's cooling system.

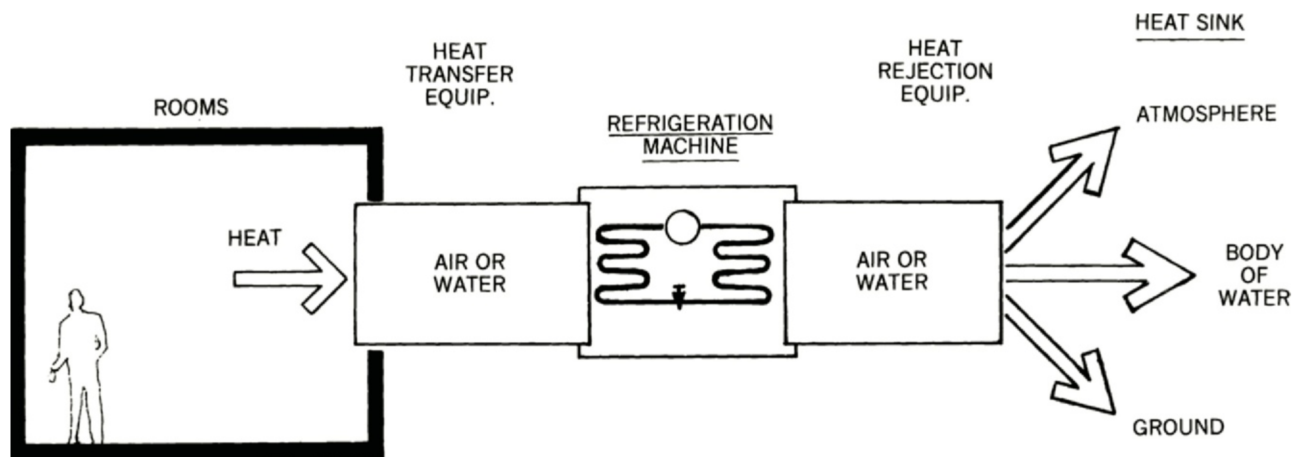


Figure 16.12b Cooling systems vary mainly in how heat is transferred to and from the refrigeration machine.

the outdoor air passes directly over the condenser coil (Fig. 16.13a). Direct refrigerant units are appropriate for cooling small to medium-sized spaces or zones that require their own separate mechanical units.

All-Air Systems

In an all-air system, air is blown across the cold evaporator coil and then delivered by ducts to the rooms that require cooling (Fig. 16.12c). Air systems can effectively cool, heat, ventilate, filter, and dehumidify air. The main disadvantages are the bulky ductwork and large fan power required.

All-Water Systems

In an all-water system, the water is chilled by the evaporator coil and then delivered to fan-coil units in each space (Fig. 16.12d). Although the piping in the building takes up very little space, the fan-coil units in each room do require some space.

Another advantage of the all-water system is the small amount of energy required by the pumps as compared with fans. However, since ventilation must be supplied from windows, the all-water system is usually not suitable for interior rooms.

Combination Air-Water Systems

An air-water system is a combination of the above-mentioned air and water systems (Fig. 16.12e). The bulk of the cooling is handled by the water and fan-coil units, while a small air system completes the cooling and also

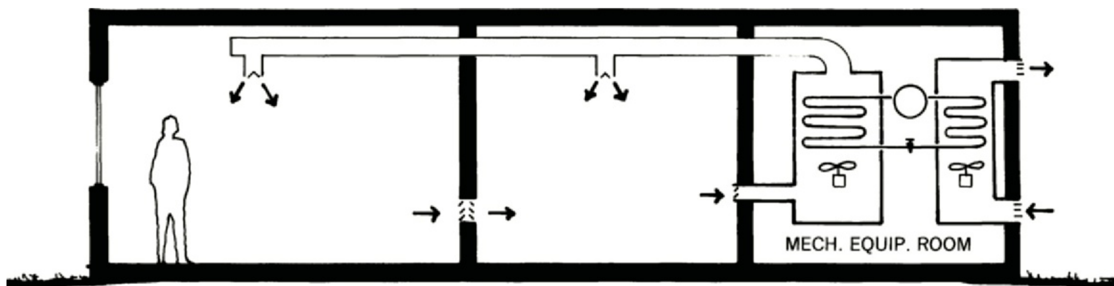


Figure 16.12c A schematic diagram of an all-air system is shown.

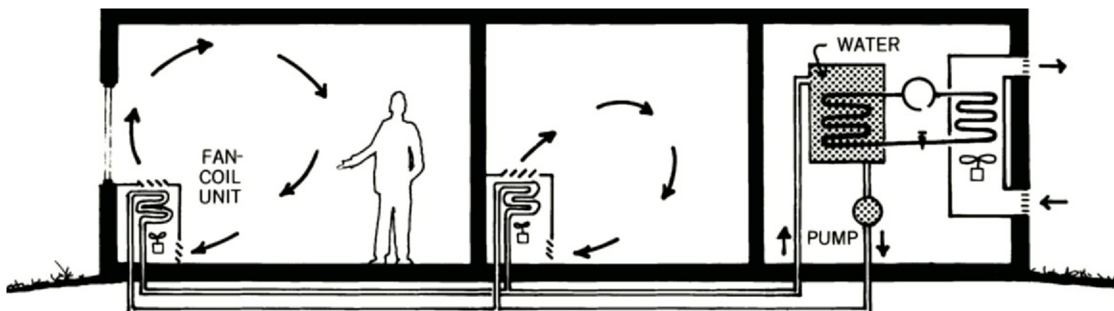


Figure 16.12d A schematic diagram of an all-water system is shown. Because the refrigeration machine in this case chills water, it is called a chiller. Note that with this system the interior room lacks ventilation.

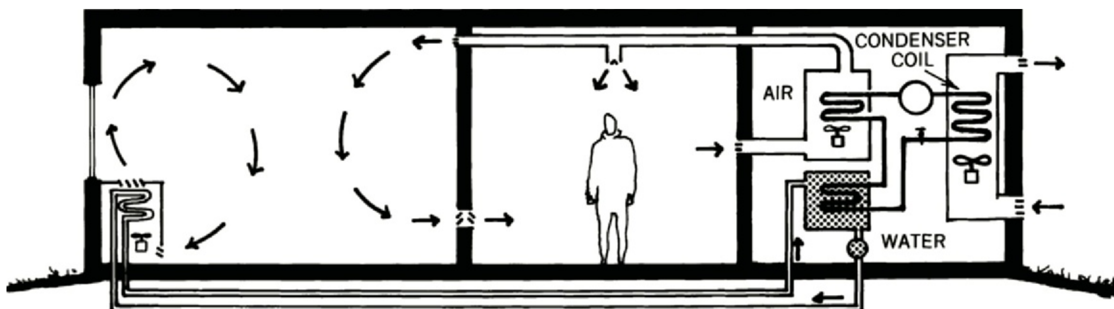


Figure 16.12e A schematic diagram of an air-water system is shown. Note that, unlike all-water systems, this system provides ventilation to all rooms.

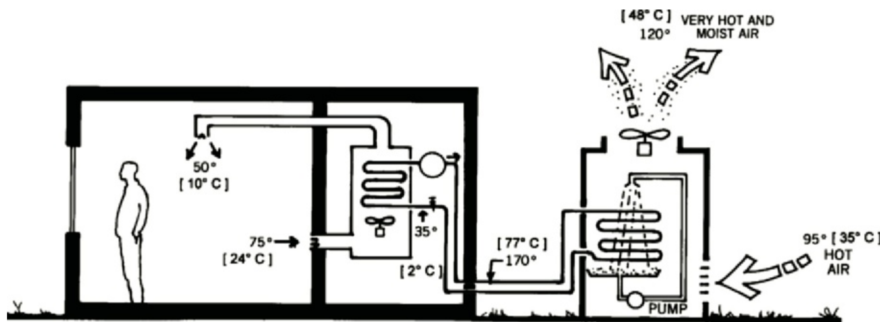


Figure 16.12f In an evaporative condenser, water is sprayed over the hot condenser coils to more efficiently dump heat into the atmosphere.



Figure 16.12h In urban areas, cooling towers are typically located on rooftops. The cooling towers can be recognized by their circular fan housings.

ventilates, dehumidifies, and filters the air. Since most of the cooling is accomplished by the water system, the air ducts can be quite small.

Heat-Dumping Systems

The above systems describe how heat is transferred from building spaces to the refrigeration machine. The following discussion describes how the heat from the refrigeration machine is dumped into the atmospheric heat sink.

In small buildings, the heat given off by a refrigeration machine is usually dumped into the atmosphere by blowing outdoor air over the condenser coil (Fig. 16.12e). To make this heat transfer more efficient, water can be sprayed over the condenser coil. Medium-sized buildings often use a specialized piece of equipment called an **evaporative condenser** to dump heat into the atmosphere by evaporating water (Fig. 16.12f). Some water must be continuously supplied to replace the water lost by evaporation. Since refrigerant lines are limited in length because of pressure loss due to friction, an evaporative condenser cannot be more than about 60 ft (18 m) from the compressor and evaporator coil. Thus, for large buildings, cooling towers are frequently a better choice.

A **cooling tower** also dumps heat into the atmosphere via the evaporation of water. However, the evaporating water is used to cool more water rather than the refrigerant, as in the evaporative condenser. This cooling water is then pumped to the refrigeration machine, where it cools the condenser coil (Fig. 16.12g). Although much of the water is recirculated, some makeup water is again required to replace the water lost by evaporation. Most cooling towers are placed on roofs (Fig. 16.12h), but when

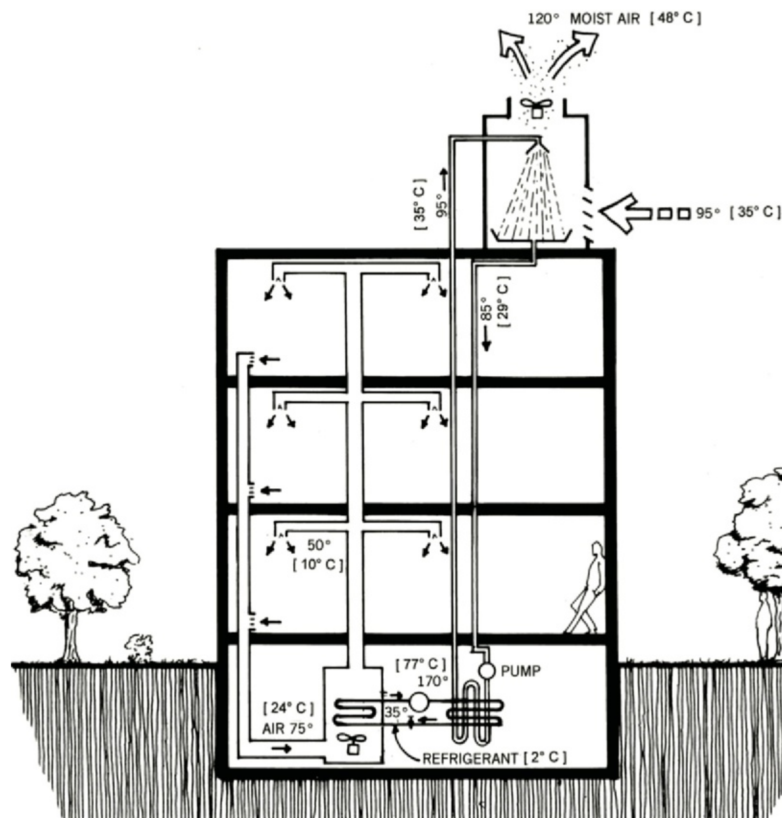


Figure 16.12g A cooling tower cools water via evaporation. This cooling water is then used to cool the condenser coil located elsewhere.

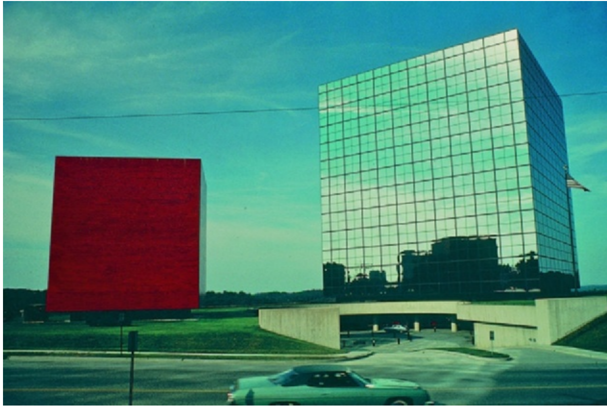


Figure 16.12i The small raised cube at the left is a cooling tower for this office building, the Blue Cross and Blue Shield Building in Towson, Maryland. Air is pulled in at the bottom and blown out the top.



Figure 16.12j These decorative fountains are used in place of a cooling tower at the West Point Pepperell factory in Lanett, Alabama.

land is available, they can be equally well placed at grade (Fig. 16.12i). As a matter of fact, a cooling tower does not have to be a structure at all. A decorative fountain can be a very effective substitute for a cooling tower (Fig. 16.12j).

16.13 AIR-CONDITIONING FOR SMALL BUILDINGS

Air-conditioning is the year-round process that heats, cools, cleans, and circulates air. It also ventilates and controls the moisture content of the air. The various conceptual components of air-conditioning systems have been described above. Some of the most common air-conditioning systems will now be described first for small or one-story buildings and then for large, multistory buildings.

Through-the-Wall Unit

For air-conditioning single spaces like motel rooms, a **through-the-wall unit** also known as a **PTAC (packaged terminal air conditioner)** is often used. Each of these units essentially consists of a compressive refrigeration machine (Fig. 16.13a).

The condenser coil, compressor, and one fan are on the exterior side of an internal partition. The compressor is on the outside because it is the noisiest part of the equipment. On the interior side of the partition, there is the evaporator coil and a fan to blow air over it. As indoor air passes over the evaporator coil, its temperature is often lowered below its dew-point temperature, thereby dehumidifying the air. Consequently, condensation occurs, and the condensate must be collected and disposed of. Often, the condensate is used to help cool the condenser coil. An adjustable opening in the interior partition allows a controlled amount of fresh air to enter for ventilation purposes. Return air from the room first passes over a filter. An electric-strip heater is sometimes supplied for cold weather. Often, however, a heat pump is used instead of just a refrigeration machine for more efficient winter heating. The electric-strip heaters are then still included but are used for backup heating only when the outdoor temperatures are too low for the heat pump.

Packaged Systems

Like the previously described unit, **packaged systems** are preengineered, self-contained units where most of

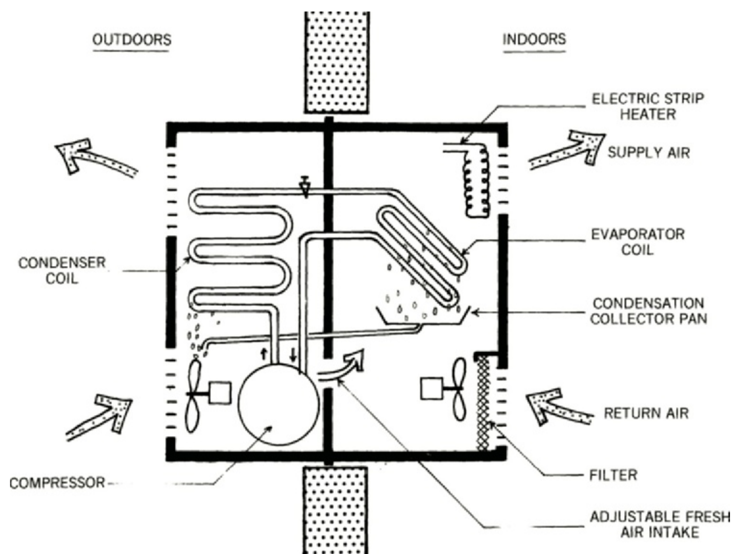


Figure 16.13a A schematic diagram for a through-the-wall air-conditioning unit that can heat as well as cool is shown.

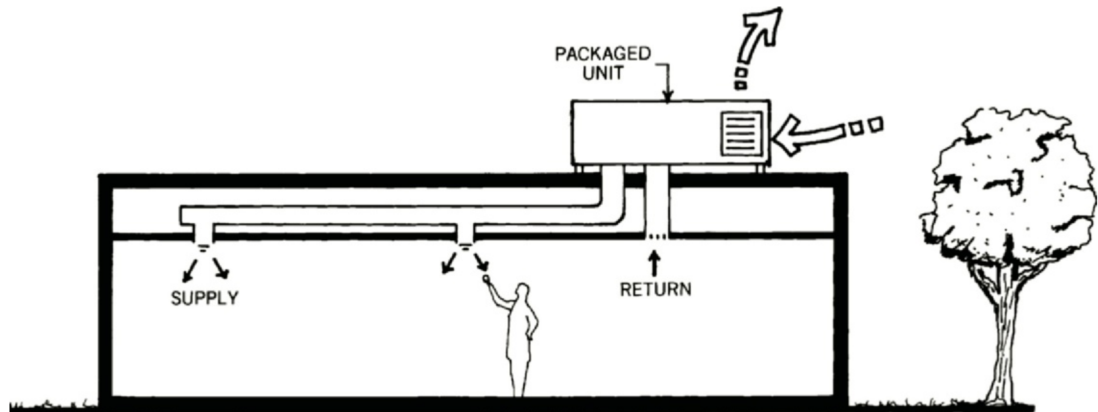


Figure 16.13b A packaged unit can contain both heating and cooling equipment.

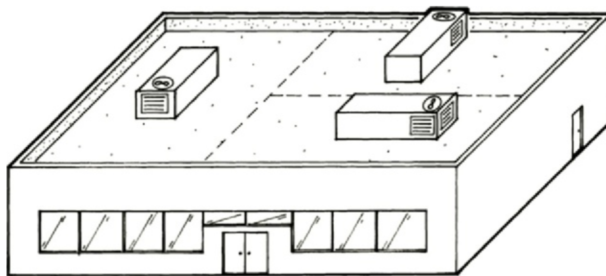


Figure 16.13c Rooftop packaged units are placed over the separate zones that they serve.

the mechanical equipment is assembled at the factory. Everything is in one unit except for the site-installed ducts. Consequently, these systems offer low installation, operating, and maintenance costs. Usually, small buildings are served by one package, while larger buildings get several. Rooftop versions are the most common, with each unit serving a separate zone (Figs. 16.13b and 16.13c). Packaged units are sometimes also used on the ground for buildings with crawl spaces (Fig. 16.13d), above a suspended ceiling when there is enough space (Fig. 16.13e), or in an attic.

Packaged units can also heat a building via electric strips, a heat pump, or a gas furnace. Electric-strip heaters are appropriate only in very mild climates. As mentioned before, heat pumps are an economical way to heat in much of the United States. In very cold climates, gas is the logical source of heat for the packaged units.

Split Systems

Most homes and many other small to medium-sized buildings find the split system to be most appropriate. In this system, the compressor and condenser coils are in an outdoor unit, while the **air-handling unit (AHU)** with the evaporator coil is indoors (Fig. 16.13f). As in all cooling systems, condensation from the evaporator coil must be drained away. The air-handling unit also contains the central heating system. As with packaged

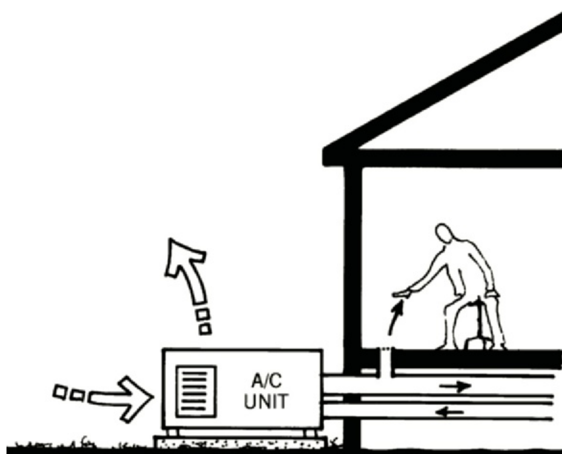


Figure 16.13d A packaged unit designed for crawl-space construction is shown.

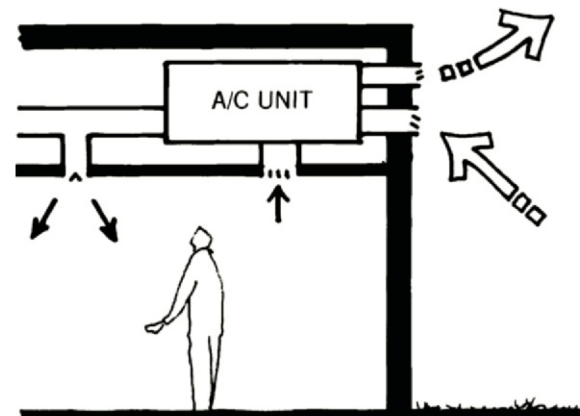


Figure 16.13e A packaged unit designed for placement above a suspended ceiling or in an attic is shown.

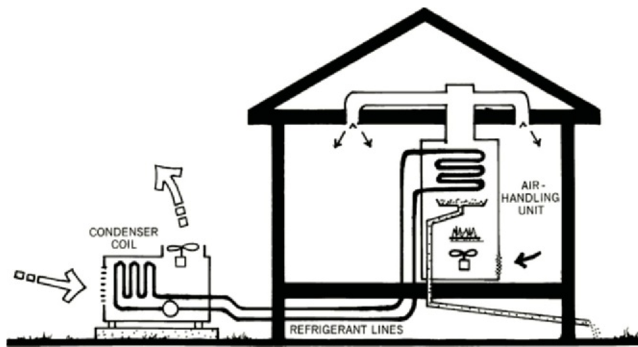


Figure 16.13f A schematic diagram of a split system is shown in this section.

units, the heating is usually by electric strips, a heat pump, or a gas furnace.

Figures 16.13g and 16.13h illustrate the use of split systems for a small office building. The compressor/condenser units are shown on grade, although they could equally well be on the roof if free land were not available. The air-handling units with their evaporator coils and heating systems are in a **mechanical-equipment room (MER)**. The supply ducts are above a suspended ceiling but on the indoor side of the roof insulation. Thus, any heat loss from the ducts is into the air-conditioned space. The air is supplied to each room through a top register (high on the wall) or a ceiling diffuser. Return-air grilles and ducts bring the air back to the air-handling units. In homes, instead of grilles, smaller rooms often have undercut doors to allow air to enter the corridor, which can act as a return-air **plenum** (duct). Sections of both supply and return ducts are lined with sound-absorbing insulation to trap noise emitted by the air-handling units. A short piece of flexible duct (Fig. 16.13h) prevents vibrations from the air-handling unit from being transmitted throughout the building by the duct system. Ventilation is maintained by means of exhaust fans in the toilets and an

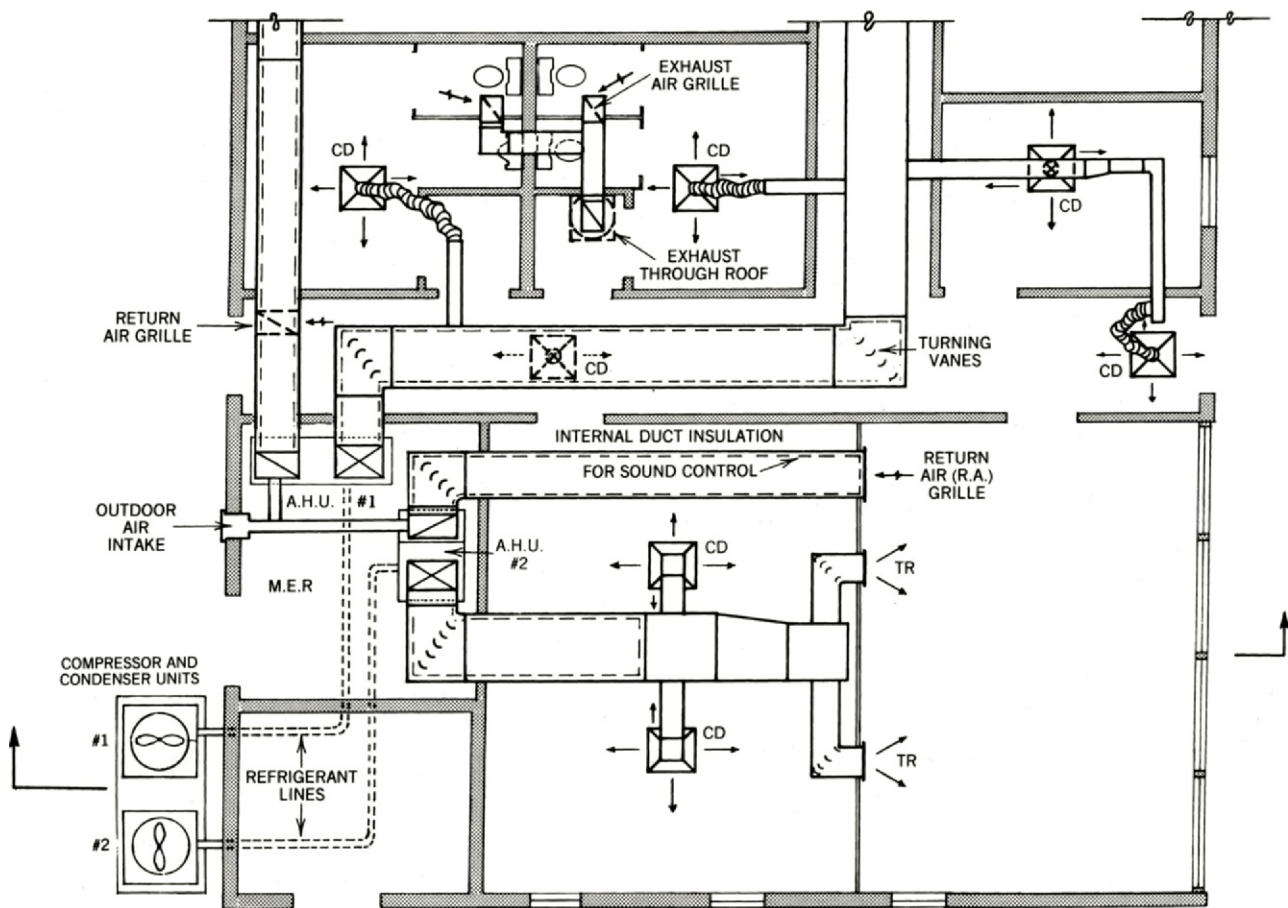


Figure 16.13g This plan shows a small two-zone office building served by two split systems. Double diagonal lines define supply ducts in section, while a single diagonal line across a rectangle defines a return duct. Abbreviations: TR = top register, CD = ceiling diffuser, M.E.R. = mechanical equipment room, A.H.U. = air-handling unit.

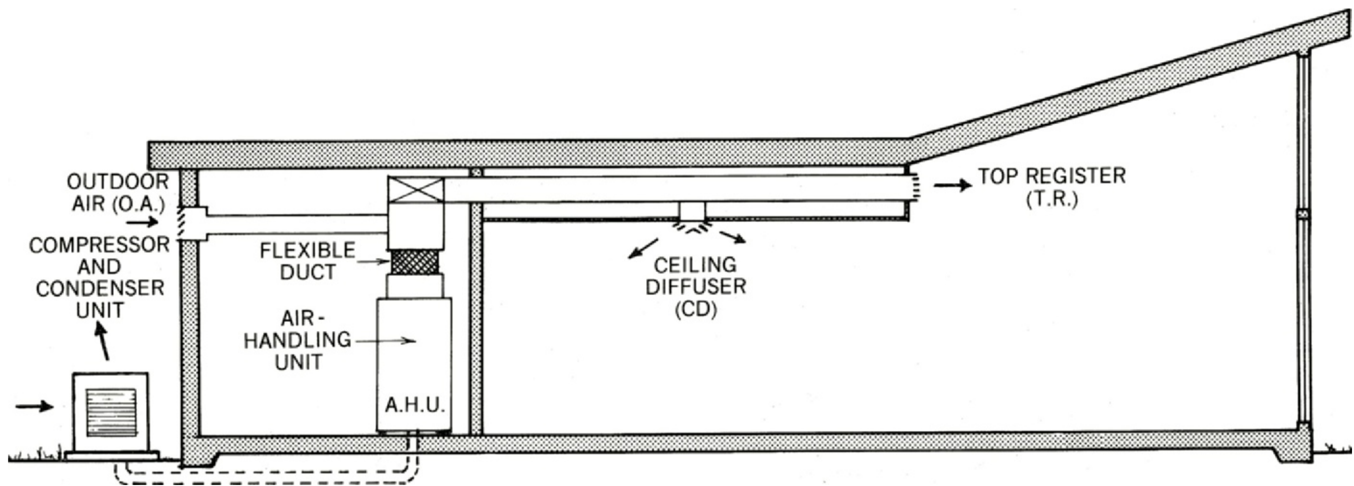


Figure 16.13h See the plan above for the location of this section.

outdoor-air intake into the return ducts in the MER.

The split system is very flexible because only two small copper tubes carrying refrigerant must connect the outdoor condenser/compressor with the indoor air-handling unit. However, these units cannot be much more than 60 ft (18 m) apart. Thus, the split system is appropriate for small to medium-sized buildings. Usually separate zones are served by having their own split units (Fig. 16.13i).

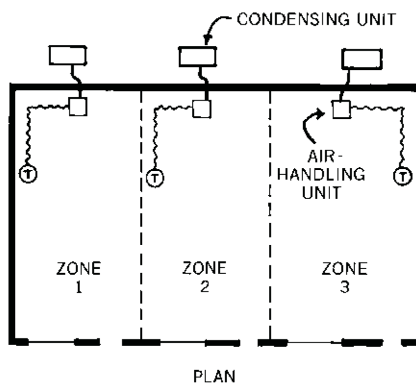


Figure 16.13i Each zone has its own split system controlled by a separate thermostat.

Ductless Split Systems

It is often difficult, if not impossible, to hide ducts when adding air-conditioning to an existing building that has either inadequate or no air-conditioning. Ducts are especially difficult to conceal in historic-preservation work. Ductless split systems require only two small copper refrigerant lines between the outdoor compressor/condenser unit and the mini indoor air-handling units (Fig. 16.13j). The indoor units are compact, unobtrusive, and very quiet. The attractive indoor units are usually placed high on a wall, where they are out of the way and effective, and where condensation in the units can be easily drained away. They are operated by remote control units much like those used to control electronic equipment. One compressor/condenser unit can serve up to four mini air-handling units as much as 160 ft (50 m) away. However, they are appropriate only for rooms with windows, since they do not introduce outside air.

Although ductless split systems have been popular in much of the world for more than twenty years, they are now also becoming popular in the United States not only for renovations but also for new construction. They are easy to install and avoid the problems that come with ductwork. They are most appropriate for buildings with small spaces that have windows, such as hotels, apartment buildings, and small office buildings

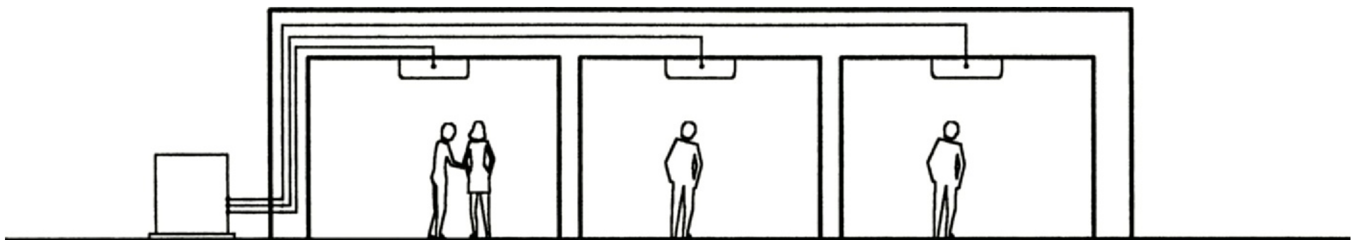


Figure 16.13j Ductless split systems are most advantageous in renovation work where ducts are hard to install or hide. One compressor/condenser unit can feed up to four mini air-handling units, which are usually mounted high on a wall but can also be mounted on the ceiling.

with multiple tenants. Ductless split systems come in three varieties: mini-split, multi-split, and variable refrigerant flow.

The mini-split, as its name implies, is for small installations. The system would have one compressor condenser unit outdoors and up to four air handlers indoors. The multi-split variety is for larger installations with as many as fifty air-handling units and one or more compressor/condenser units tied together in parallel.

A recent development is a multi-split system with **variable refrigerant flow (VRF)**, sometimes also called variable refrigerant volume (VRV). To maintain the indoor temperature, a VRF system adjusts the flow rate of the refrigerant, which is much more efficient than cycling on and off as is the case with conventional systems.

When used in buildings with nonoperable windows or for interior spaces, a small ventilation-only duct system can be added. Such ducts would be significantly smaller than conventional ducts.

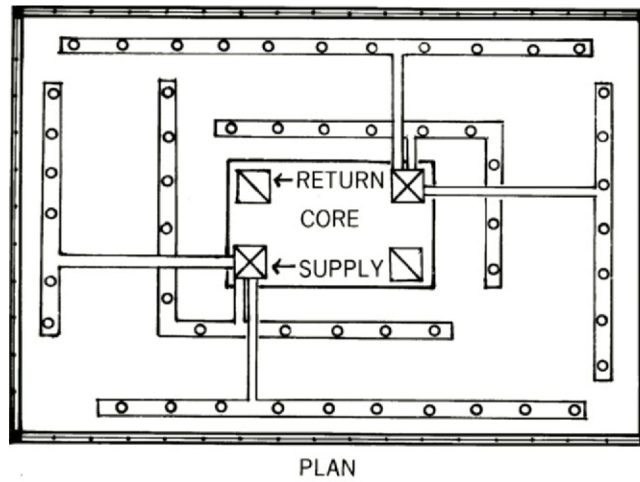


Figure 16.14b A typical air-distribution plan with all risers in the core results in duct crossings and consequently a greater floor-to-floor height.

16.14 AIR-CONDITIONING FOR LARGE MULTISTORY BUILDINGS

Most large multistory buildings use highly centralized air-conditioning equipment. The roof and basement are the usual choice for these **central station systems** (Fig. 16.14a). The basement has the advantage of easy utility connections, noise isolation, not being valuable rental area, and the fact that structural loads are not a problem. The roof, on the other hand, is the ideal location for fresh-air intakes and heat rejection to the atmosphere. Since cooling towers are noisy, produce very hot and humid exhaust air, and can produce fog in cold weather, they are usually placed on the roof. In many buildings, the equipment is divided, with some in the basement and some on the roof. To minimize the space lost to vertical air ducts, intermediate mechanical floors are used in very high buildings (Fig. 16.14a). If there is sufficient open land, the cooling tower and some of the other equipment might be placed on grade adjacent to the building (Fig. 16.12i).

In plan, most large multistory buildings have windows on all four sides and a core area for building services (Fig. 16.14b). Floor-to-floor heights of 13 or 14 ft (about 4 m) are often necessary to accommodate the horizontal ducts bringing

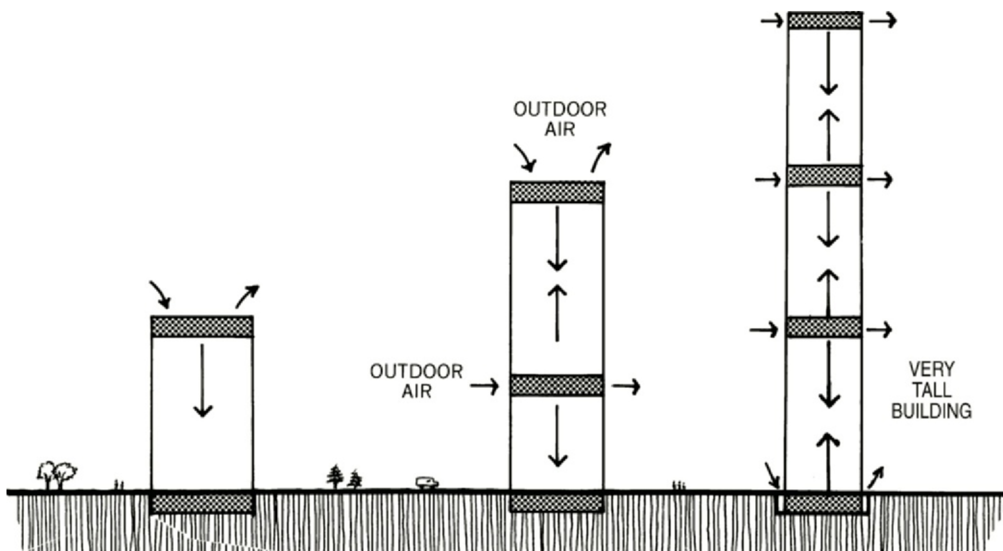


Figure 16.14a Common locations for centralized mechanical-equipment spaces in large multistory buildings are shown.

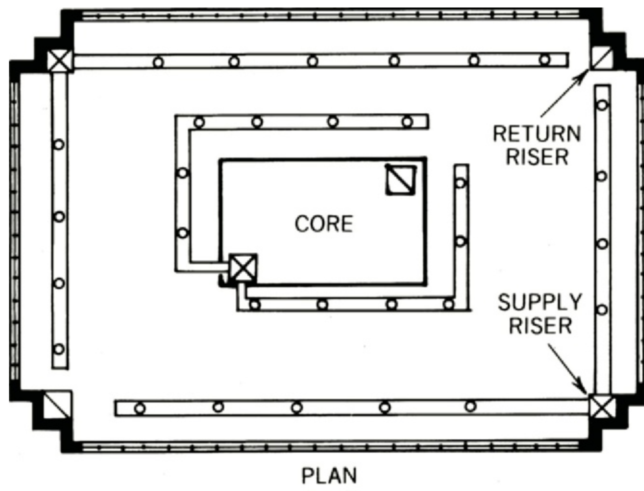


Figure 16.14c One way to minimize floor-to-floor height is to supply the perimeter zones with separate perimeter risers. These ducts can be expressed on the facade.

conditioned air from the core to the perimeter. Lower floor-to-floor heights are possible with water-based systems or if the perimeter area is supplied with riser ducts at the outside wall (Fig. 16.14c).

When choosing a mechanical system for a building, one must consider the following: initial cost, life-cycle costs, energy consumption, space requirements, comfort level, and number of zones required. Both comfort and energy efficiency are greatly affected by the number of zones created. Since zones are expensive, however, their number is usually kept to a minimum. As was explained earlier in this chapter, the average large building has at least five zones because of orientation.

For the purpose of clarity, an example building with only three zones will be used to illustrate the major mechanical systems for large multistory buildings (Fig. 16.14d). It could represent either a corner lot or one quadrant of a building with windows on all four sides. A section of this building is shown in Figure 16.14e. As is typical in many tall office buildings, the mechanical equipment is shown to be on the roof. This section shows an all-air system served by a single central air-handling unit on the roof. To avoid the large vertical ducts, separate air-handling units could be placed on each floor, with only hot and cold water circulating vertically (Fig. 16.14f). This alternative saves a great deal of energy because moving air great distances requires about twenty times more power than moving water.

The major mechanical systems available for large office buildings are illustrated by showing a typical floor plan and section of each. The equipment shown in each floor plan is above the ceiling unless otherwise noted. These systems are grouped by the heat-transfer medium used: all-air, air-water, and all-water.

Air systems are of two types: constant-air-volume (CAV) and variable-air-volume (VAV). In CAV systems,

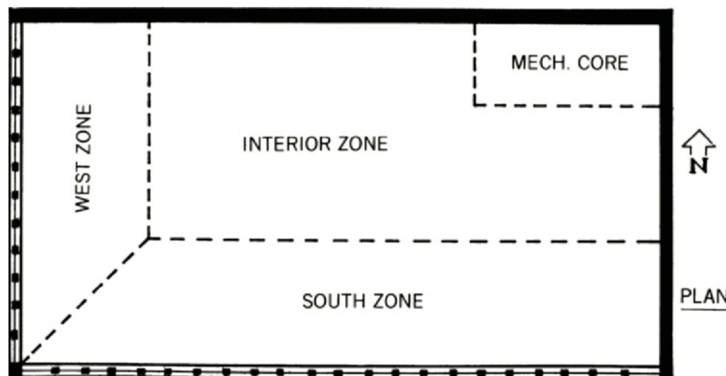


Figure 16.14d A special three-zone floor plan is used to illustrate the major mechanical systems available for large buildings. This plan could represent the southwest quadrant of a typical large office building.

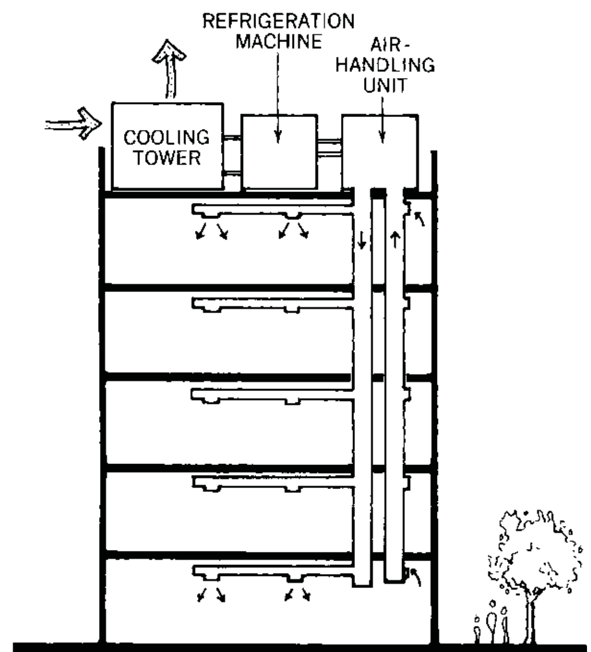


Figure 16.14e This section shows a typical multistory building with a rooftop central-station mechanical system. In this case, the air-handling unit on the roof serves all floors.

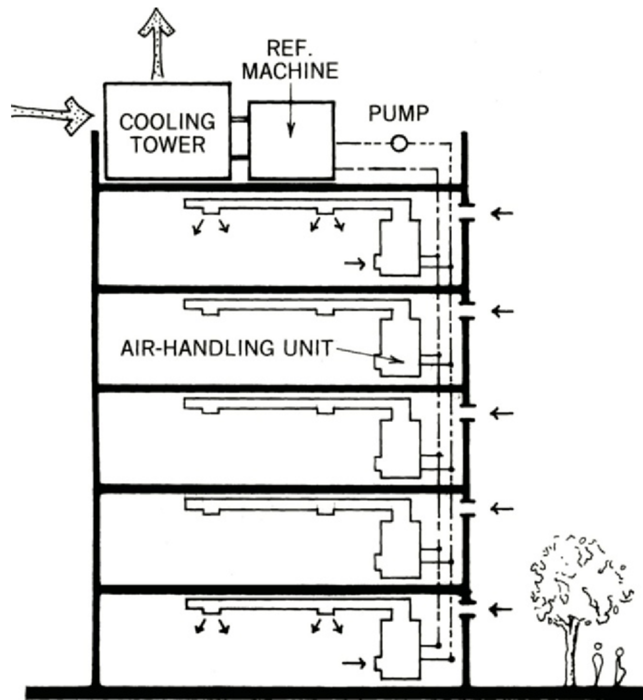


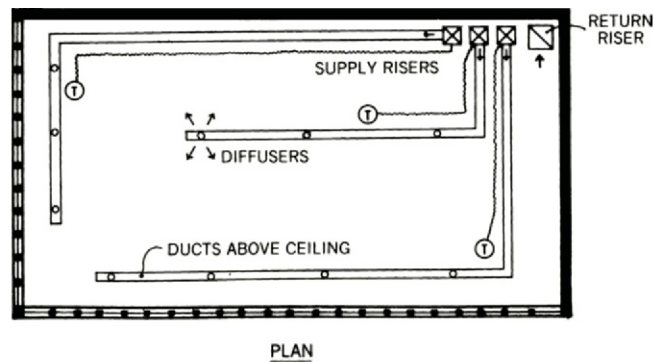
Figure 16.14f This section shows an alternate approach. Although much of the mechanical equipment is still on the roof, each floor has a separate air-handling unit. Because the refrigeration machine is now producing chilled water, it is called a chiller.

1. *Single-duct system with CAV*. The single-duct system is basically a one-zone system. Since a separate supply duct and air-handling unit is required for each zone, this system is most appropriate for small buildings or for medium-sized buildings with few zones (Fig. 16.14g).
2. *VAV system*. This is a single-duct system that can easily have many zones. A variable-volume control box is located wherever a duct enters a separate zone (Fig. 16.14h). A thermostat in each zone controls the airflow by operating a damper in the VAV control box. Thus, if more cooling is required, more cool air is allowed to enter the zone. Since VAV systems cannot heat one zone while cooling another, they are basically cooling-only systems. Because heating is usually required only on the perimeter, a separate heating system can be supplied in

the temperature control of a space is achieved by changing the temperature of a constant supply of air. In VAV systems, the temperature and humidity control of a space is achieved by varying the amount of supply air delivered to each space at a constant temperature. VAV systems are more widely used because they are more versatile and efficient than CAV systems.

All-Air Systems

The great advantage of all-air systems is that complete control over air quality is possible. The main disadvantages are that all-air systems are very bulky and a significant part of the building volume must be devoted to the delivery of air. They are also less efficient because moving large quantities of air requires a great deal of power. It must be noted that for clarity, only the supply ducts are shown on each plan in the following examples. There could also be a sizable return-duct system on each floor.



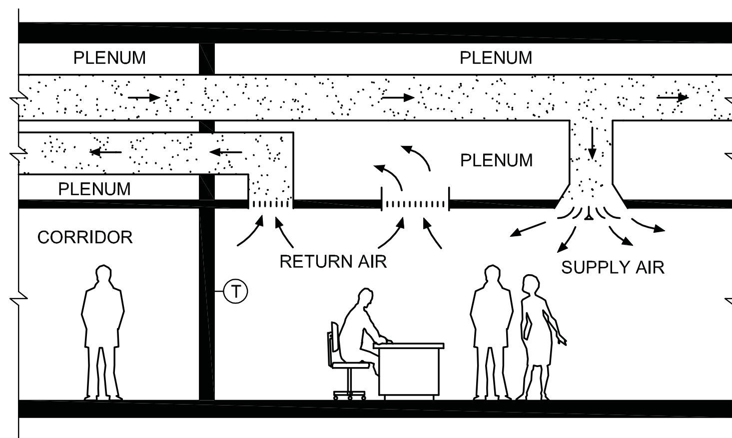


Figure 16.14g The single-duct system. Return air can travel either through the above-ceiling plenum or through the return air duct shown in the section.

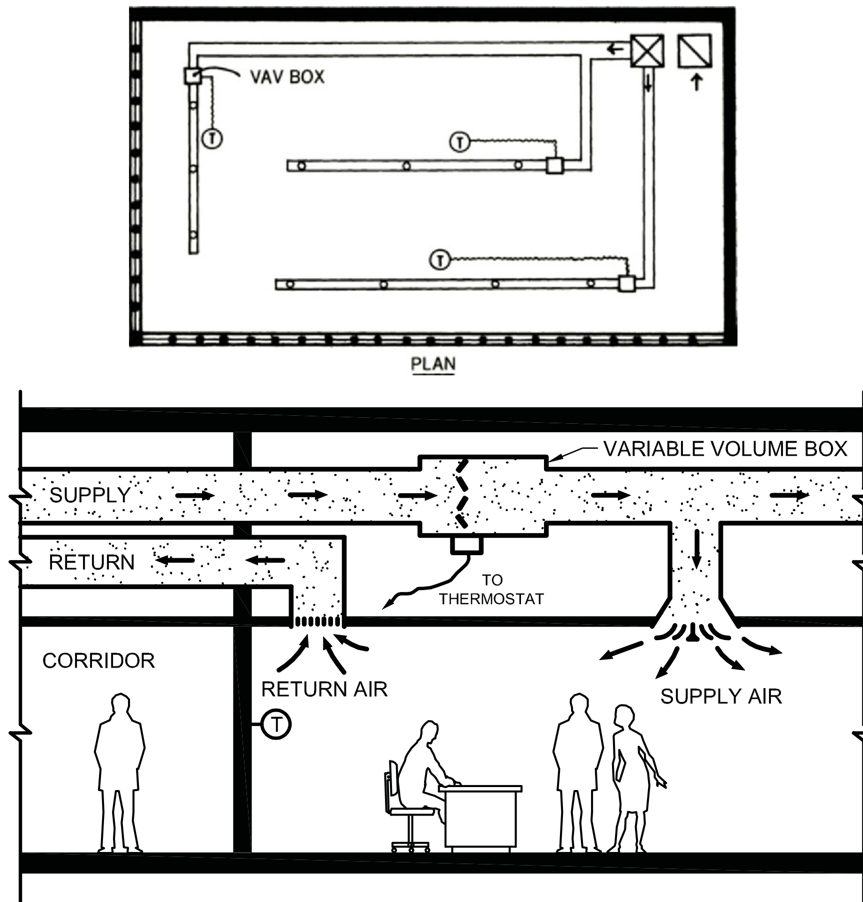


Figure 16.14h The variable-air volume (VAV) system. Note the VAV control boxes for each zone.

conjunction with the VAV system. The low first-cost and low energy usage make the VAV system very popular, and it is applicable to almost every building type.

3. *Terminal reheat system (CAV)*. At first, the terminal reheat system looks just like the VAV system previously described, but, in fact, it is very different. Instead of VAV boxes, this system has terminal reheat boxes in which electric-strip heaters or hot-water coils reheat air previously cooled (Fig. 16.14i). For example, on a spring day, the zone with the greatest cooling load will determine how much the air for the whole building is cooled. All other zones will then reheat the cold air to the desired temperature. Thus, most of the building is being heated and cooled simultaneously—a waste of energy. This system was popular in the past because it gave excellent temperature control. It should not be used now except in special cases because of its high energy consumption. Terminal reheat systems can also be of the VAV type. In this case, the terminal reheat box also controls the volume of air. Thus, the control of space temperature is handled efficiently by varying the volume of the supply air, and the reheat function is called for only when some space needs heating while the others all need cooling.
4. *Multizone system*. In this mechanical system, every zone receives air at its required temperature through a separate duct (Fig. 16.14j). These ducts are supplied by a special multizone air-handling unit that custom-mixes hot and cold air for each zone. This is accomplished by means of motorized dampers located in the air-handling unit but controlled by thermostats in each zone. Depending on the temperature, the ratio of hot and cold air varies

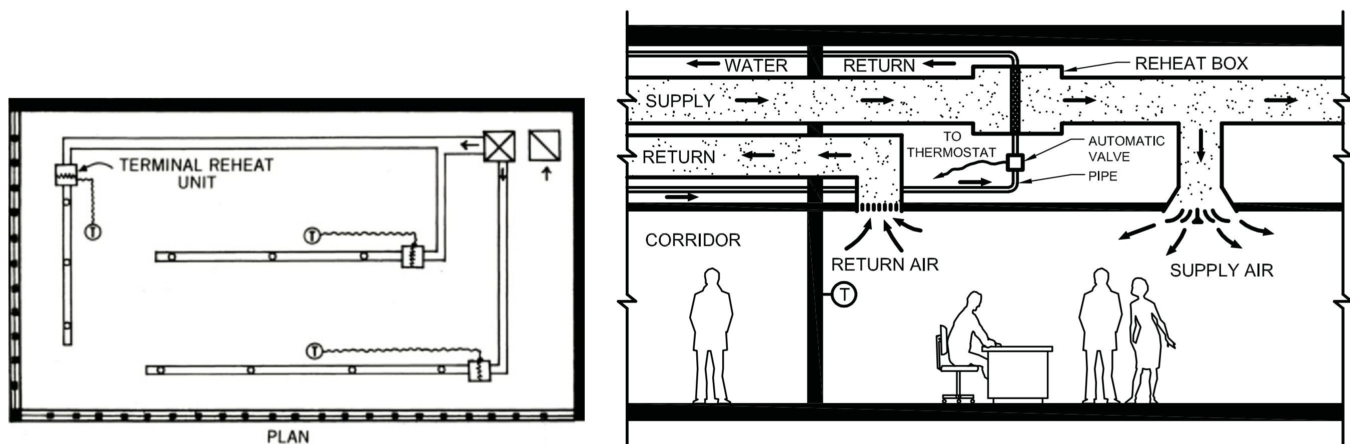
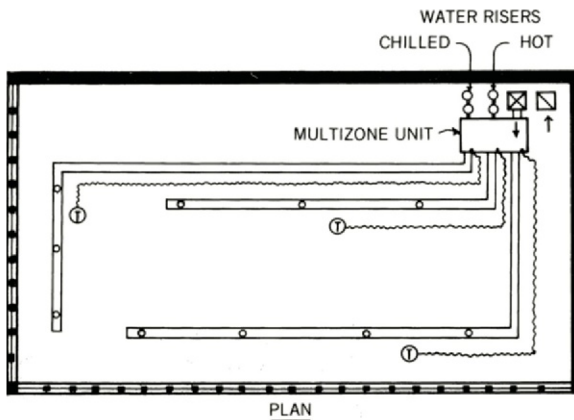


Figure 16.14i The terminal reheat system. Note the terminal reheat boxes for each zone.



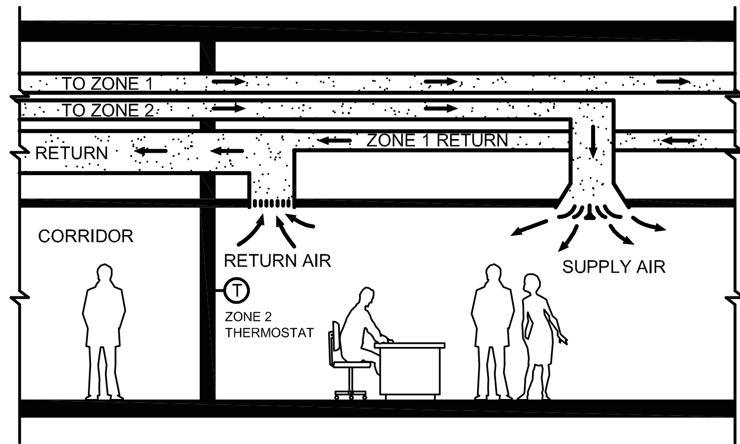
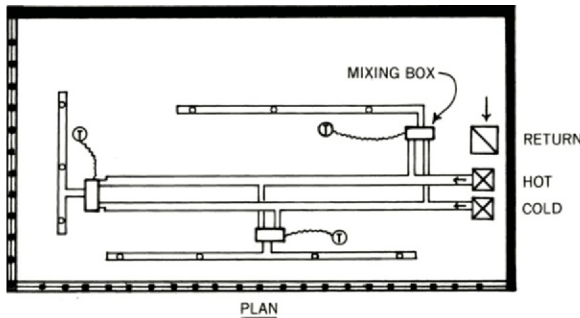


Figure 16.14j The multizone system is shown. Note that each zone has its own supply duct.



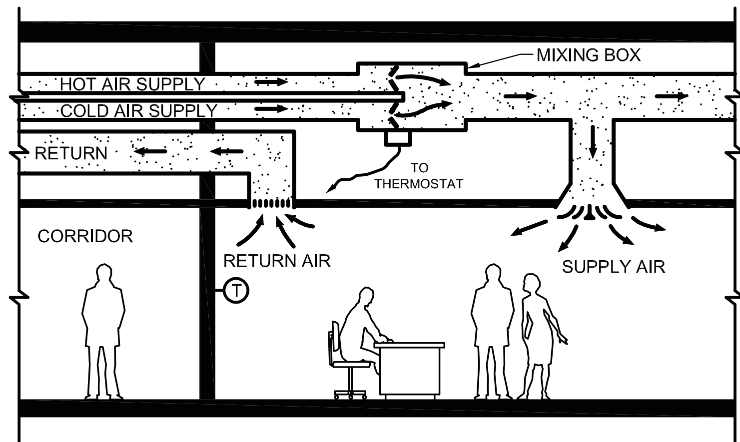


Figure 16.14k The double-duct system. Note the mixing boxes for each zone.

but the total amount of air is constant. The multizone unit is supplied with hot water, chilled water, and a small amount of fresh air.

Each multizone unit can handle up to about eight zones or about 30,000 ft^2 (2800 m^2). Because moderate air temperatures are created by mixing hot and cold air. this system is also wasteful of energy. First costs also are relatively high because of the duplication of ducts.

5. *Double-duct system*. Like the multizone system, the double-duct system mixes hot and cold air to achieve the required air temperature. Instead of mixing the air at a central air-handling unit, mixing boxes are dispersed throughout the building (Fig. 16.14k). Thus, there is no limit to the number of zones possible. However, two sets of large supply ducts are necessary.

   Although the double-duct system creates a high level of thermal comfort and allows for great zoning flexibility, it is very expensive, requires much building space, and is wasteful of energy.

Air-Water System

The following systems supply both air and water to each zone of a building. Although this increases the complexity of the mechanical systems, it greatly decreases the size of the equipment because of the immense heat-carrying capacity of water as opposed to air. Air is supplied mainly because of the need for ventilation.

1. *Induction system*. In an induction system, a small quantity of high-velocity air is supplied to each zone to provide the required fresh air and to induce room air to circulate (Fig. 16.14l). Most induction units are found under windows, where they can effectively neutralize the heat gain or loss through the envelope (Fig. 16.14m). As the high-velocity air shoots into the room, it induces a large amount of room air to circulate. This combination of room air (90 percent) and fresh air (10 percent) then passes over heating or cooling coils. Thus, most heating or cooling is accomplished with water, while ventilation and air motion are accomplished with a small amount of high-velocity air. Local thermostats regulate the temperature by controlling the flow of either hot or cold water through the coils.

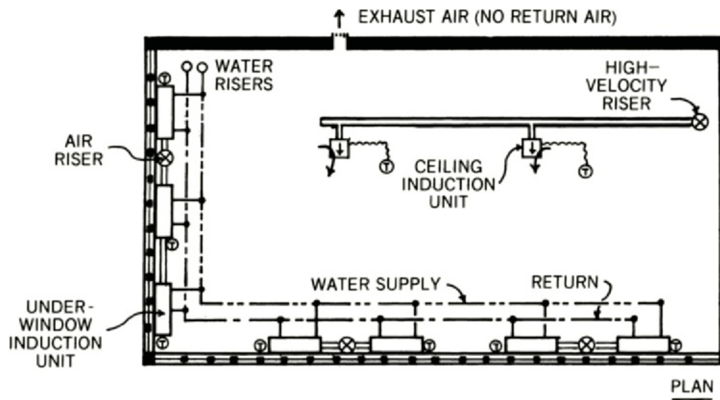


Figure 16.14l In the induction system, high-velocity air is supplied at the perimeter to the induction units, where it is heated or cooled by the water system.

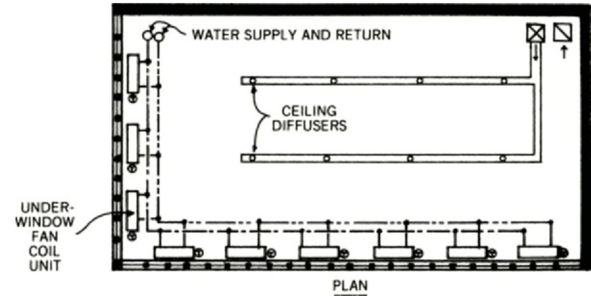


Figure 16.14n A fan-coil with supplementary air system is shown. The fan-coil units can be either above or below the windows.

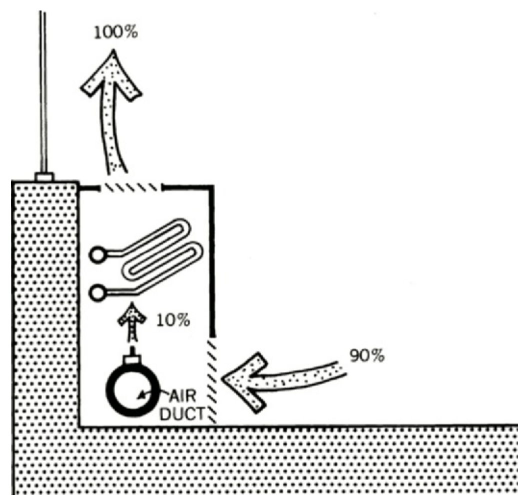


Figure 16.14m A section of an induction unit with cooling or heating coils is shown.

Unfortunately, high-velocity (up to 6000 ft/min [30 m/s]) and, therefore, high-pressure ducts are much more expensive than regular-velocity (up to 2000 ft/min [10 m/s]) ducts. High-velocity air systems also consume much more fan power than normal-velocity systems. Because of these problems, induction systems are little used today.

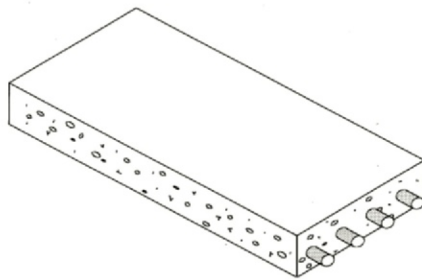
2. *Fan-coil with supplementary air*. This system also consists of two separate parts. For ventilation and cooling of the interior areas, there is an all-air system, and for neutralizing the heat gain or loss through the envelope, there are fan-coil units around the perimeter (Fig. 16.14n). The fan-coil units are described in more detail below under all-water systems.

3. *Radiant panels with supplementary air*. Similar to radiant heating but in reverse, a cool surface can achieve thermal comfort by lowering the MRT. Moderately cool panels (about 65°F [18°C]) will suffice if their area is large. The ceiling is the best surface for radiant cooling because it is large, it is unobstructed by furniture, and it can also cool by convection. Figure 16.14o shows three radiant cooling systems. Indoor rain from condensation on the ceiling can be prevented by controlling the humidity and panel temperature. The supplementary air is dehumidified in order to control indoor humidity, and the large cooling panels are maintained above the dew-point temperature of the air. Cooling with a radiant ceiling works best in dry climates and is most problematic in very humid climates, especially if the windows can be opened.

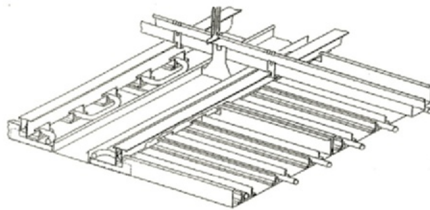
4. *Active chilled beams*. Unlike a cold radiant ceiling, chilled beams cool by convection. Cold water passing through a finned coil will cool the warm air collecting at the ceiling. The cool air then sinks to the floor, pulling more warm air across the finned coils (Fig. 16.14p). When ventilation air is supplied by ducts, it can be used to induce much more room air to pass over the cooling coils. In that case the device is called an active rather than passive chilled beam.

Chilled beams can be recessed in a suspended ceiling or hang free. They can be multiservice by incorporating lighting, sensors, and sprinklers (Fig. 16.14q). Since there is forced ventilation air, the active chilled beams can also be used for heating.

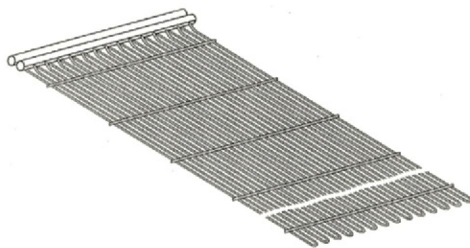
Like cooling with a radiant ceiling, chilled beams work best in dry climates, but they can also be used in humid climates if the indoor humidity can be kept low enough. Controlling humidity in very



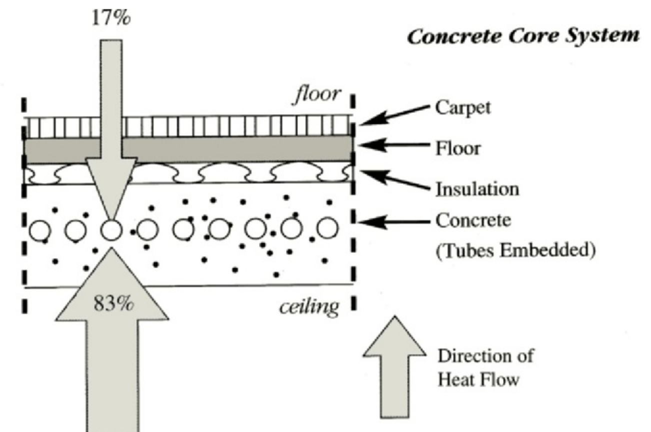
A ***core-cooled*** *ceiling is the cooling equivalent of a floor heating system. In this system, water is circulated through plastic tubes embedded in the core of a concrete ceiling. This layout allows the system to take advantage of the storage capacity of the concrete and provides the opportunity to shift the building peak load away from the utility grid peak.*

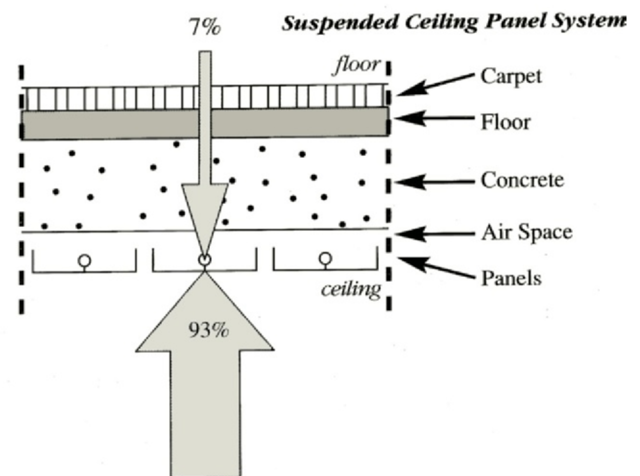


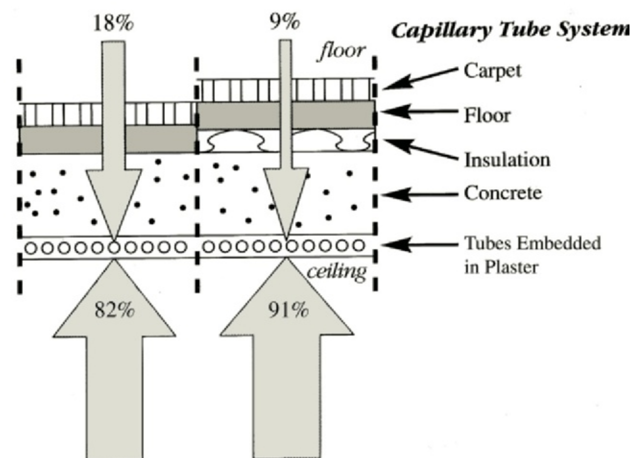
The most used system is the ***panel system.*** *It is usually built from aluminum panels, with metal tubes connected to the rear of the panel. An alternative is to build a "sandwich system," in which the water flow paths are included between two aluminum panels. The use of a highly conductive material in the panel construction provides the basis for a fast response of the system to changes in room loads.*



Cooling grids made of ***capillary tubes*** *placed close to each other can be embedded in plaster, gypsum board or mounted on ceiling panels. This system provides an even surface temperature distribution. Due to the flexibility of the plastic tubes, cooling grids might be the best choice for retrofit applications.*







As shown by the arrows, most of the cooling effect occurs on the ceiling side of radiant panels.

Figure 16.14o Three different radiant cooling systems are shown. (From Lawrence Berkeley Laboratory, *Center for Building Science News*, Vol. 1, no. 4, Fall 1994.)

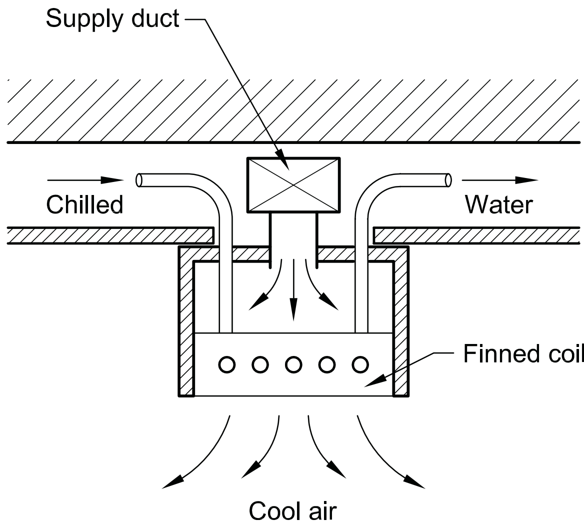


Figure 16.14p In an active chilled beam system, ventilation is used to induce the warm air collecting near the ceiling to pass across the cold finned coils. The fast moving ventilation air also spreads the cooled air over a larger floor area.



Figure 16.14q Multiservice active chilled beams can also provide lighting, sensors, and sprinklers. (Courtesy of Trox UK Ltd.)

humid climates requires an airtight envelope, nonoperable windows, and minimum moisture production indoors (i.e., no fountains or extensive vegetation). Passive chilled beams will be discussed under all-water systems below.

All-Water Systems

Since these systems supply no air, they are appropriate when a large amount of ventilation either is not necessary or can be achieved locally by such means as opening windows.

1. *Fan-coil system*. The fan coil-unit, as the name implies, basically consists of a fan and a coil within which water circulates. The units are often in the form of cabinets for placement under windows (Fig. 16.14r). The fan blows room air across coils through which either hot or cold water circulates. Thermostatically controlled valves regulate the flow of water through the coils. A four-pipe system, which is shown, has two pipes for hot-water supply and return and another two pipes for cold-water supply and return. Thus, either heating or cooling is possible at any time of year. In the less expensive but also less comfortable two-pipe system, hot water circulates during the winter and cold water in the summer. In such systems, it is not possible for an occupant to choose either heating or cooling. A three-pipe (hot, cold, and a common return) system also exists but wastes energy because hot and cold water return through the same pipe.

   Condensation on the cooling coils must be collected in a pan and drained away. When the fan-coil unit is on an outside wall, it is possible to have an outdoor air intake connected to the unit. A three-speed fan switch or thermostat allows occupants to have control over the temperature.

   Fan-coil units are most appropriate for air-conditioning buildings with small zones, such as apartments, condominiums, motels, hotels, hospitals, and schools. Besides the under-window location, fan-coil units are sometimes located above windows (valance units), in small closets, or in the dropped ceiling above a bathroom or hallway (Figs. 16.14s and 16.14t. Fan-coil units come in many shapes and configurations to allow great flexibility in their use.

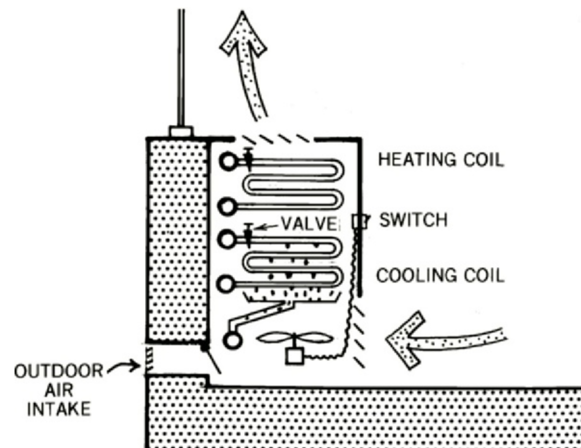


Figure 16.14r This is a schematic diagram of an under-window fan-coil unit (four-pipe system) with outdoor air intake and a condensation drain.

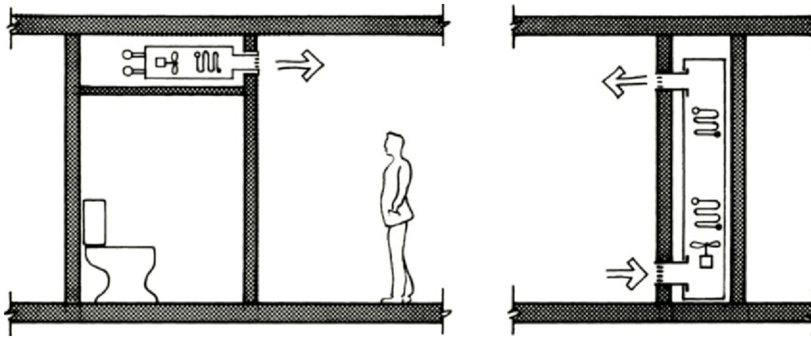


Figure 16.14s Fan-coil units can also be placed above a dropped ceiling or in a small closet.

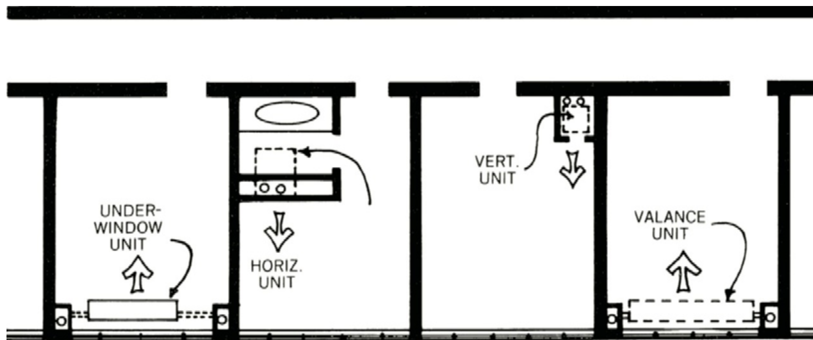


Figure 16.14t Four alternate fan-coil systems are shown in plan view: (1) under-window unit, (2) above-bathroom ceiling unit, (3) closet unit, and (4) valance (above-window) unit.

2. *Water-loop heat-pump system*. With this system, each zone is heated or cooled by a separate water-to-air heat pump. A thermostat in each zone determines whether the local heat pump extracts heat from a water loop (heating mode) or injects heat into the water loop (cooling mode) (Fig. 16.14u). The water in the loop is circulated at between 60° and 90°F (15° and 32°C). In the summer, when most heat pumps are injecting heat into the loop, the excess heat is disposed of by a cooling tower. In winter, when most heat pumps are extracting heat, a solar collector or a central boiler keeps the water in the loop from dropping below 60°F (15°C).

The water-loop heat-pump system really shines in spring and fall or whenever about half the heat pumps are in the cooling mode and the other half are in the heating mode. In that case, the heat extracted from the water loop will roughly equal the heat injected, and neither cooling tower nor boiler needs to operate. This system is most appropriate in those buildings and climates where the simultaneous heating of some zones and cooling of others is common. However, the numerous heat pumps are a major maintenance problem. A similar thing can be done by ductless split systems with a variable refrigerant flow (VRF) system (see Fig. 16.13j) but without a heat pump in every zone.

3. *Passive chilled beams*. These chilled beams are similar to the active chilled beams described above except that no air supply is used. Consequently, they work purely by natural convection (Fig. 16.14v). Because there is no forced convection to blow air down, passive chilled beams can only cool. Furthermore, it takes more passive than active chilled beams to cool an area because of the slow motion of natural convection.

See Figure 16.14w for a comparative summary of the main HVAC systems.

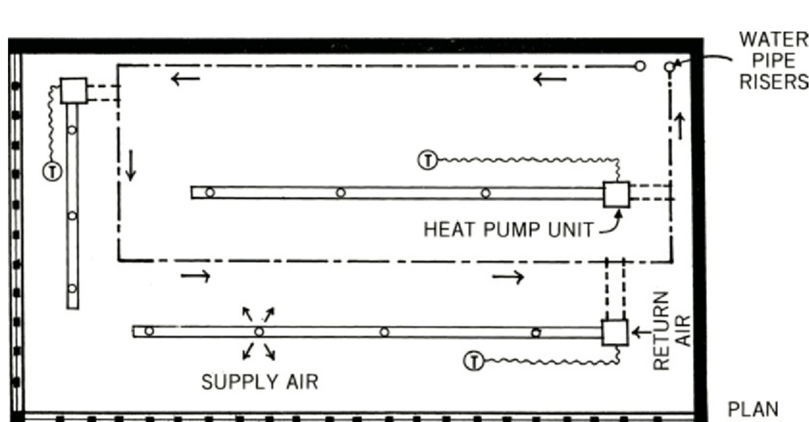


Figure 16.14u In a water-loop heat pump system, each zone has its own heat pump. All equipment is above the ceiling.

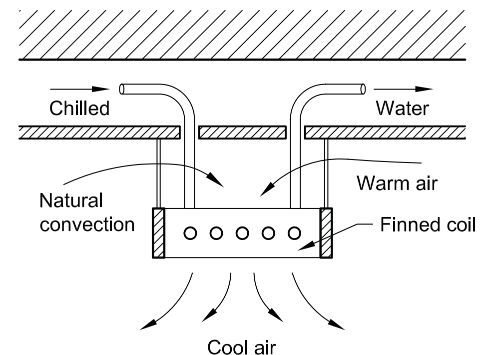


Figure 16.14v In a passive chilled beam, the room air is cooled by natural convection. As the warm air at the ceiling comes in contact with the chilled finned coil, it cools and sinks, pulling more warm air across the finned coil.

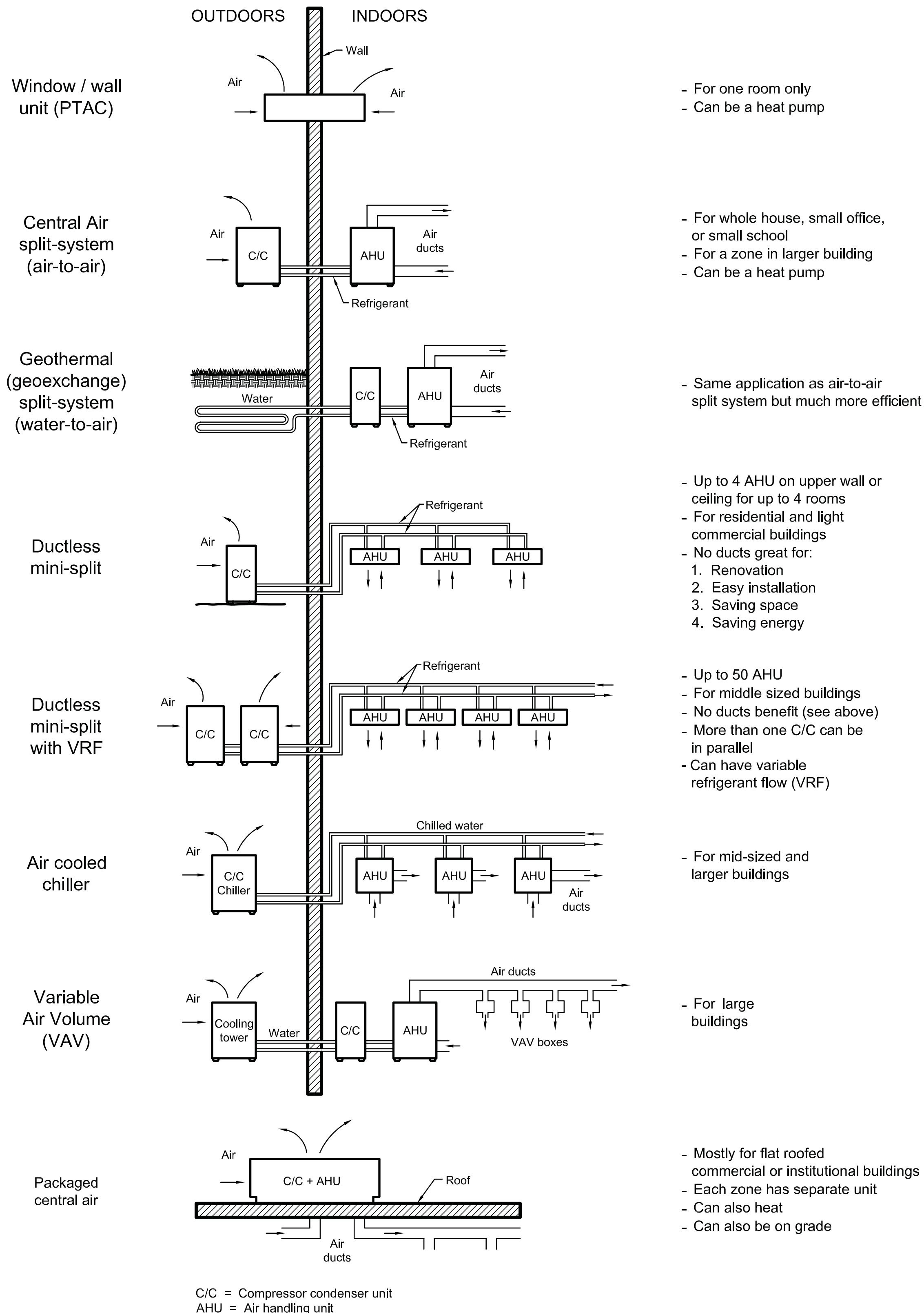


Figure 16.14w This summary presents and compares the major HVAC systems and shows which parts are outdoors and which are indoors.

16.15 DESIGN GUIDELINES FOR MECHANICAL SYSTEMS

Because the mechanical and electrical equipment requires 6 to 9 percent of the total floor area of most buildings, sufficient and properly located spaces should be allocated for it. By incorporating the following rules and design guidelines at the schematic design stage, one can prevent many serious design problems later on.

Sizing Guidelines

For the floor-area and ceiling-height requirements of the various parts of a mechanical system, see Table 16.15A. Note that the spatial requirements for the air-handling units depend mostly on whether an all-air, air-water, or all-water system is used. Ducts for horizontal air distribution are usually above the ceiling and, therefore, do not use up any of the floor area. However, since floor-to-floor heights are very much dependent on the size of horizontal ducts, use Table 16.15B for a rough early estimate of duct sizes.

Location Guidelines

I. For medium-sized buildings:
   1. Place the equipment on the roof; or
   2. Use a **mechanical equipment room (MER)** centrally located to minimize duct sizes, and place it along an outside wall for easy servicing (Fig. 16.15a).

II. For large multistory buildings:
   1. Place the centralized mechanical equipment in the basement, on the roof, or on intermediate floors (Fig. 16.14a)

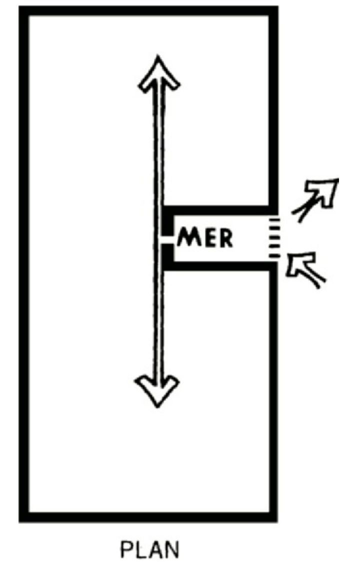


Figure 16.15a Usually, the mechanical equipment rooms (MERs) should be centrally located and have access to the outdoors.

   2. The cooling tower should be placed on the roof or on out-of-the-way adjacent land (Fig. 16.15b).
   3. Any additional MER on each floor should be centrally located to minimize duct sizes and distance air has to be moved. If these MERs require large amounts of outdoor air, they should be located along an outside wall (Fig. 16.15a).

Table 16.15A Spatial Requirements for Mechanical Equipment

Equipment Type	Floor Area Required[a] Percentage	Required Ceiling Height[b] in Feet (meters)
Room for refrigeration machine, heating unit, and pumps	1.5–4	9–18 (2.7–6)
Room for air-handling units		
All-air	2–4	9–18 (2.7–6)
Air-water	0.5–1.5	9–18 (2.7–6)
All-water	0–1[d]	N/A
Cooling tower	0.25	7–16[c] (2–5)
Packaged (rooftop)	0–1	5–10[c] (1.5–3)
Split units	1–3	8–9 (2.4–2.7)

[a]The required floor area is a percentage of the gross building area served (parking is excluded). Use the upper end of the range for small buildings and for large buildings with a great deal of mechanical equipment (e.g., laboratories and hospitals).

[b]Use the lower end of the range in ceiling height for smaller buildings.

[c]Since cooling towers and packaged units are usually not roofed over, the heights given are for the actual equipment, not ceiling height.

[d]The required area refers to fan-coil units.

Table 16.15B Cross-Sectional Area of Supply Ducts (Horizontal or Vertical)*

System	Cross-Sectional Duct Area of Conditioned Space per 1,000 ft²	100 m²
All-air	1–2 ft²	0.1–0.2 m²
Air-water	0.3–0.8 ft²	0.03–0.08 m²

*When used, return ducts are at least as large as these supply ducts. Use the large end of the range for spaces with large cooling loads or when ductwork has many turns. For the vertical-shaft space, use about twice the area of the duct risers.

Noise Guidelines

1. Equipment placed outside can be a major source of noise to neighbors.
2. Surround the MER with massive material to stop sound and vibration transmission.
3. MERs and ducts should be lined with sound-absorbing insulation.
4. Do not locate the MER near quiet areas like library reading areas and conference rooms.

Residential Guidelines

1. Use 1 ton (3.5 kW) of cooling capacity for each 500 ft^2 (45 m^2) of a standard house.

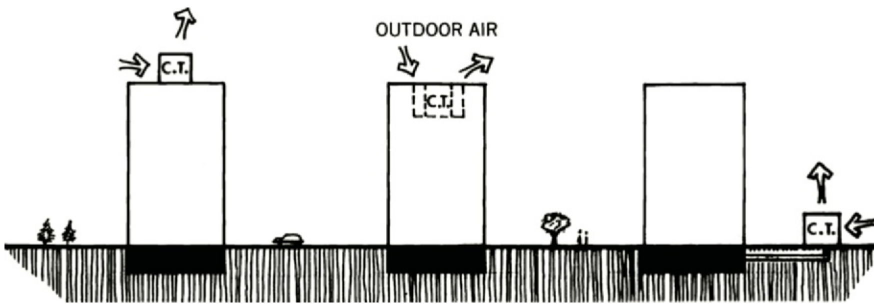


Figure 16.15b When the mechanical equipment is mainly in the basement, the cooling tower should still be on the roof or on an out-of-the-way location with good outdoor air circulation.

2. Use 1 ton (3.5 kW) of cooling capacity for each 1000 ft^2 (90 m^2) of a modern, well-designed, and well-built house.

General Guidelines

1. The duct layout should be orderly and systematic, like the structural system.
2. Avoid air ducts crossing each other.
3. Provide adequate access to large equipment that might have to be replaced.

16.16 AIR SUPPLY (DUCTS AND DIFFUSERS)

Air is usually supplied to rooms by means of round, rectangular, or oval ducts. However, building elements such as hollow-core concrete planks and hollow beams can also be used. Although round ducts are preferable for a number of reasons, they require clearances that are not always available. Consequently, rectangular ducts are very popular. However, the ratio of short to long sides, the aspect ratio, should not exceed 1:5 because the resulting high airflow friction requires the ducts to have excessively large areas and perimeters (Fig. 16.16a).

At least another 2 in. (5 cm) must be added to the height and width when duct insulation is used. Insulation can be required for three reasons: to reduce heat gain or loss, to prevent condensation, and to control noise transmitted from one space to the next through the ducts. To prevent condensation, a vapor barrier must be on the outside of the insulation, while for noise control, the insulation must be exposed to the airstream (Fig. 16.16b). Supply and return ducts transmit sound almost equally, because sound travels about fifty times faster than the velocity of air in ducts.

Although the size of ducts can be decreased by increasing the air velocity, there are two important reasons for using large ducts and the resultant low-velocity airflow. High-velocity airflow requires significantly more fan power to generate, and it is much noisier than low-velocity air flow.

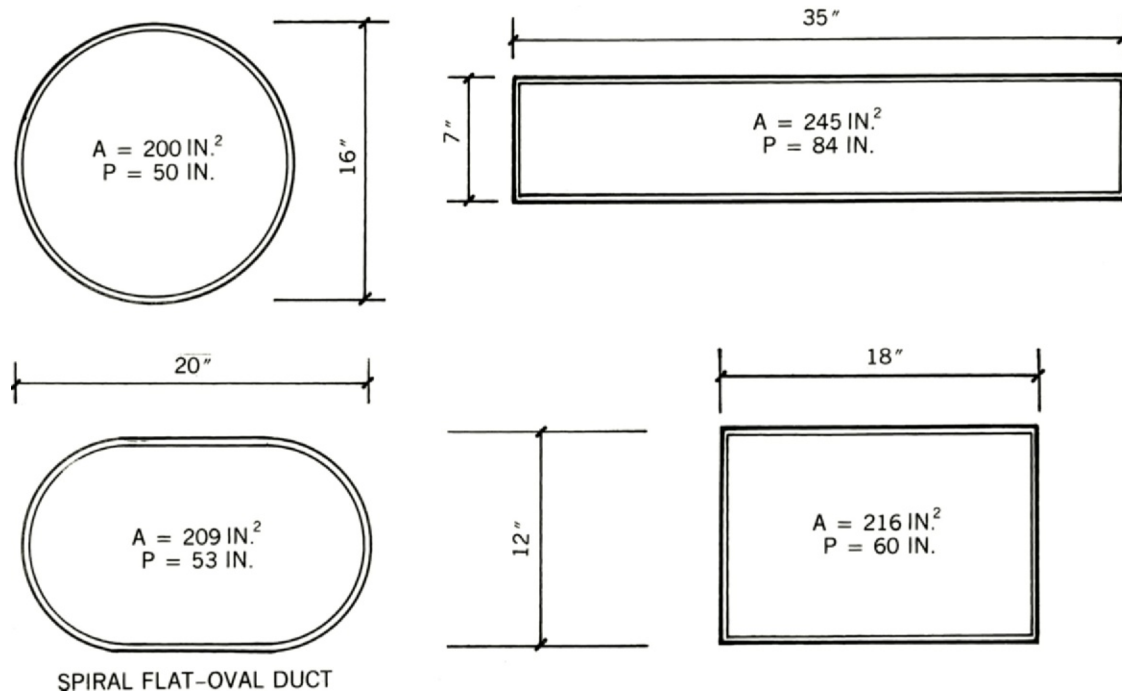


Figure 16.16a All these ducts have the same friction and, therefore, airflow capacity. The circular duct requires the least volume and material but has the greatest depth. (A = area, P = perimeter). In this example, the actual sizes are not important—only the relative sizes.

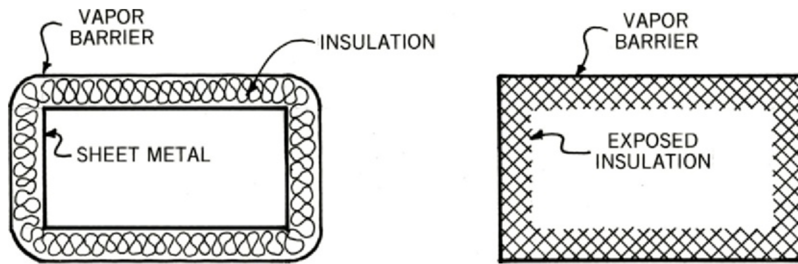


Figure 16.16b To prevent condensation on ducts, a vapor barrier must always be placed on the outside of the insulation. For noise control, porous fiberglass insulation must be exposed to the airstream.

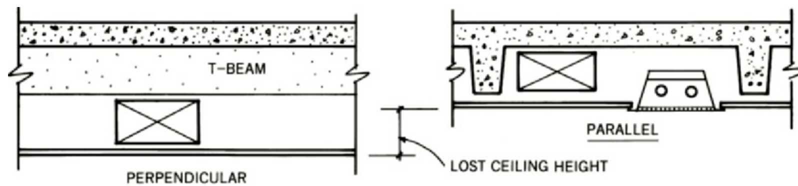


Figure 16.16c Coordinate ducts with beams and lighting fixtures to minimize the space required for the mechanical and electrical systems. Ducts should run parallel to beams.

A duct system is often described as a "tree system" in which the main trunk is the largest duct and the branches get progressively smaller (Fig. 16.14e). As much as possible, ducts should run parallel to deep structural elements and lighting fixtures to prevent wasted space when various building elements cross each other (Fig. 16.16c).

Sometimes the return-air system has a duct "tree" as extensive as that of the supply-air system. Often, however, the corridor or plenum (space) above a hung ceiling is used instead of return-air ducts. To maintain acoustical privacy, short return-air ducts lined with sound-absorbing insulation should connect rooms with the plenum. Special return-air grilles with built-in sound traps are also available for doors or walls.

Supply ducts are also lined where necessary with sound-absorbing insulation to prevent the short-circuiting of sound from one room to the next. The insulation also reduces the noise transmitted through the air from the air-handling unit (Fig. 16.13g). Noise transmission along ducts can also be reduced with passive silencers (noise traps) added to the duct system (Fig. 16.16d). To prevent the ductwork itself from transmitting noise or vibration, a flexible fabric connection is used where the main ducts connect to the air-handling unit (Fig. 16.13h).

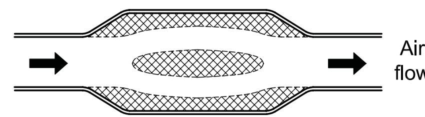


Figure 16.16d Sound traps can be added to ducts instead of lining the ducts with sound-absorbing insulation.

The supply air enters a room through a grille, a register, or a diffuser. A **supply grille** has adjustable vanes for controlling the direction of the air entering a room. A **register** is a grille that also has a **damper** behind it so that the amount as well as the direction of the air entering a room can be controlled.

In building types or climates where cooling predominates, the air is usually supplied high in each room. Although it is convenient to run ducts through an unheated attic or even on the roof, it is very undesirable from an energy point of view even if the ducts are well insulated. Thus, a dropped ceiling in the corridor is often appropriate for not only flat-roofed but also pitched-roof buildings (Fig. 16.16e).

When registers are mounted on upper walls, they are designed to throw the air about three-quarters of the distance across the room (Fig. 16.16e). When registers are mounted in the floor, under windows, or next to an outdoor wall, they are usually aimed up and, thus, are suitable only for small spaces (Fig. 16.16f). When air is supplied from the ceiling, it has to be mixed rapidly with the room air to prevent the discomfort of cold air striking the occupants; consequently, a **diffuser** is used (Fig.

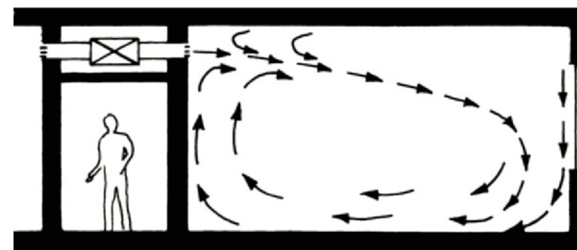


Figure 16.16e Ducts should always be on the indoor side of the thermal envelope. Above the corridor ceiling is one good location. Air from an upper-wall register should be thrown about three-quarters of the distance across a room before it drops to the level of people's heads.

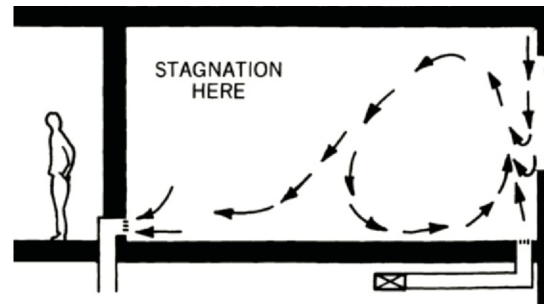


Figure 16.16f Floor registers cannot serve large spaces. They are good at countering the heating or cooling effect of windows.

16.16g). Diffusers can be round, rectangular, or linear, and, like registers, they have dampers for adjusting the volume of air being supplied. Supply air can also be diffused with large perforated ceiling panels (Fig. 16.16h).

The location of supply-air outlets is very important for the comfort of the occupants. The goal is to gently circulate all of the air in a room so that there are neither stagnant nor drafty areas. It is also important that beams or other objects do not block the air supply from reaching all parts of a room (Fig. 16.16i). Where heating is the major problem, the supply outlets should be placed low.

Diffusers and registers are unnecessary when cloth ducts are used because they supply air either by the porosity of the fabric or by small holes whose size and distribution is specified for the specific installation. Lightweight fabric ducts come rolled up and ready to be hung from the ceiling (Fig. 16.16j).

In rooms with high ceilings, it is not necessary to cool the upper layers, which, because of stratification, are very warm. Air can be introduced through low wall or floor registers. Stratification, however, is a liability in cold climates. In the winter, the hot air collecting near the ceiling of high spaces should be brought back down to the floor level by means of

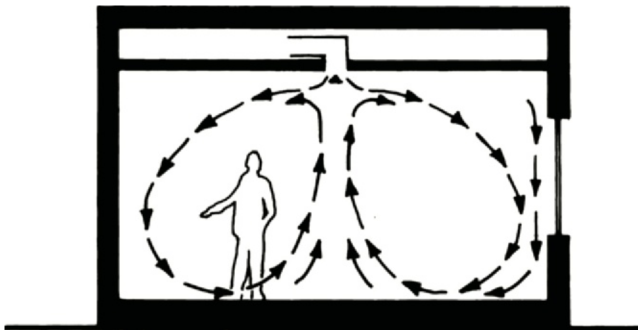


Figure 16.16g The proper airflow pattern from a ceiling diffuser is shown.

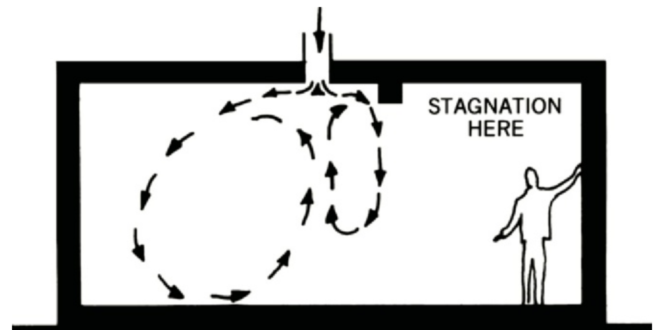


Figure 16.16i Locate air outlets carefully to avoid blocking the airflow with beams or other obstructions.

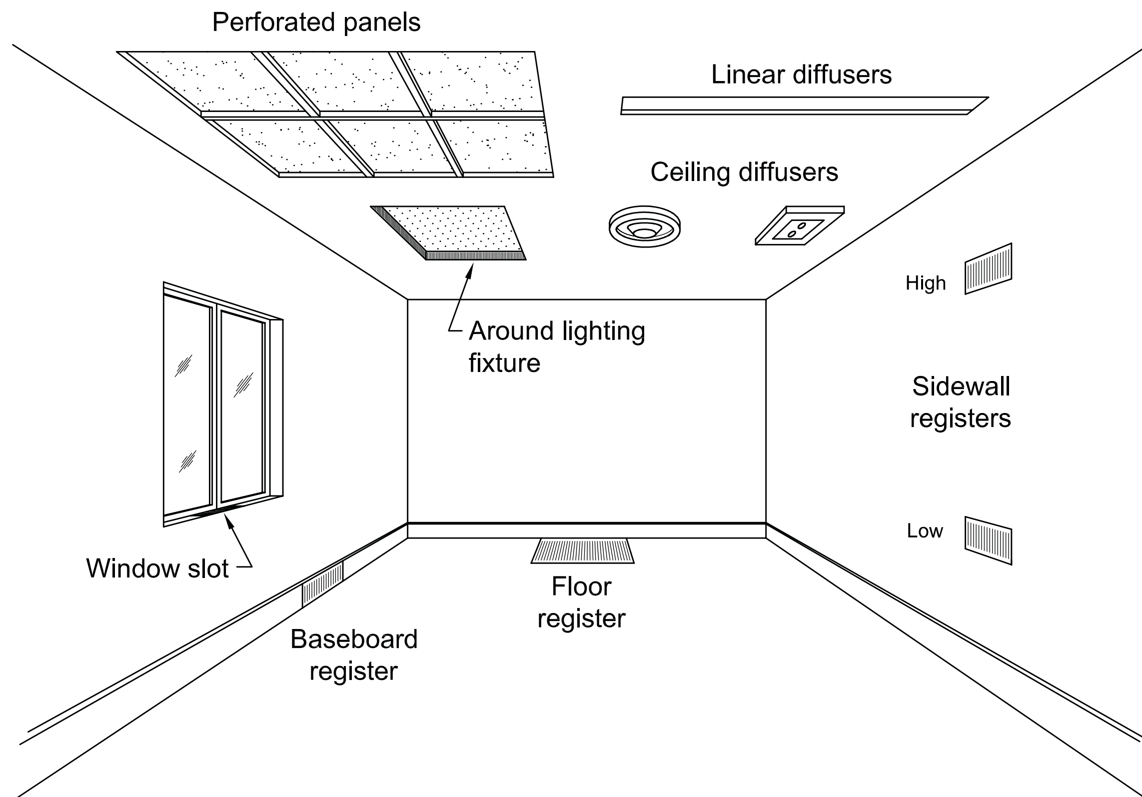


Figure 16.16h Common types of registers and diffusers are shown.



Figure 16.16j No drafts result when cloth ducts are used because the air is supplied along the entire length through the porous fabric or small holes. (Courtesy of Air Sox, Inc.)

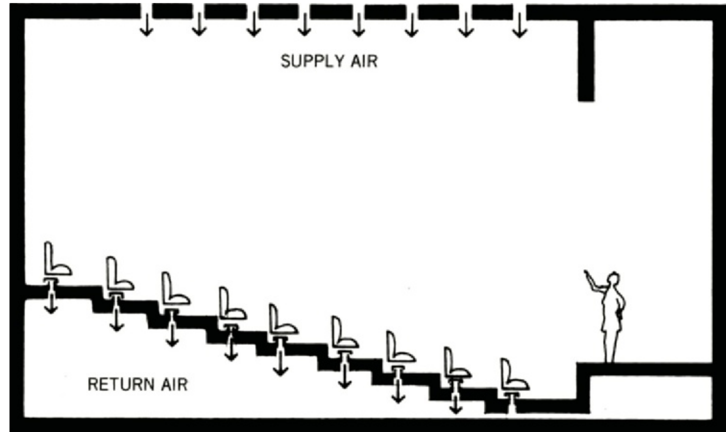


Figure 16.16l In large theaters, the air is often returned under the seating. However, reversing the flow might be even better, as is discussed under displacement ventilation.



Figure 16.16k These antistratification devices blow the hot air collecting at the ceiling down to where the people are. (Courtesy of the AirPear, www.TheAirPair.com, ©2007–2013 Airius Europe Ltd.)

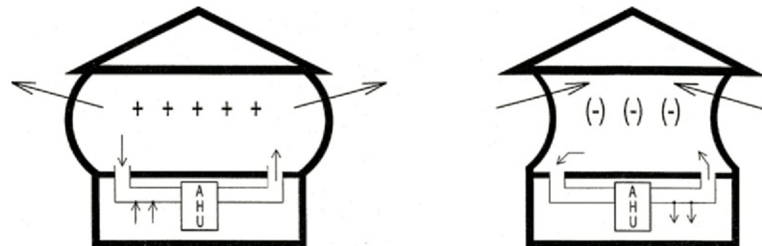


Figure 16.16m If the ducts are outside of the air-conditioned space, it is especially important to have no air leaks. Besides wasting energy, radon and toxic mildew can be sucked into the return duct or building. (After North Carolina Alternative Energy Corp. [AEC].)

antistratification ducts or devices, as shown in Figure 16.16k and Figure 10.9f. In large theaters, good results are often achieved by supplying air all across the ceiling and returning it all across the floor under the seats (Fig. 16.16l). However, using displacement ventilation might be even better. Supplying air at the floor level and returning it at the ceiling has many advantages, as described in Section 16.18.

Return air generally leaves a room through a grille, but it can also leave through lighting fixtures, perforated ceiling panels, or undercut doors in homes. The location of the return-air grille has almost no effect on room air motion if supply outlets are properly located. However, to prevent the short-circuiting of the air, do not place return openings right next to supply outlets. Also avoid return grilles in the floor because dirt is sucked into them.

When ducts run through the basement, crawl space, or attic, tight-fitting ducts are important; otherwise, the building will come under negative or positive pressure (Fig. 16.16m). If the return ducts leak, toxic material such as radon or mildew can be sucked into the return ducts. If the supply ducts leak, the building comes under negative pressure, and outdoor, attic, and crawl space air will enter through all the cracks. Since duct leaks are hard to prevent, the ducts and equipment should be placed within the thermal envelope for health as well as energy conservation reasons.

16.17 VENTILATION

The excess carbon dioxide, water vapor, odors, and air pollutants that accumulate in a building must be

exhausted. At the same time, an equal amount of fresh air must be introduced to replace the exhausted air. The air should be exhausted where the concentration of pollutants is greatest (e.g., toilets, kitchens, laboratories, and other such work areas). The air pressure in these areas should be kept slightly below that of the rest of the building to prevent the contaminated air from spreading. At the same time, the pressure in the rest of the building should be slightly above the atmospheric pressure to prevent the infiltration of untreated air through cracks and joints in the building envelope (Fig. 16.17a). These pressures can be maintained by the proper balance between the amount of air that is removed by exhaust fans and the amount brought in through the air-conditioning unit.

Normally, about 15 percent of the air circulated for heating or cooling will be outdoor air. Under certain circumstances, much larger amounts of outdoor air are introduced. For example, the American Society for Heating Refrigeration and Air Conditioning Engineers (ASHRAE) recommends five times as much outside air for smokers as for nonsmokers.

Outdoor air can also be used for cooling when its temperature is sufficiently below the indoor temperature. Mechanical systems designed to use cold outdoor air for cooling are said to have an **economizer cycle**.

Although mechanical ventilation is a standard part of air-conditioning in larger buildings, it is usually left up to natural infiltration and operable windows to ventilate smaller buildings. As long as small buildings were not very airtight, this policy worked quite well. Now, however, many small, well-constructed, airtight buildings are suffering from indoor air pollution. Even some well-ventilated large buildings have problems with indoor-air quality, especially when they are new.

Indoor-air quality (IAQ) is affected by pollution from many sources. Besides the obvious sources from people and their activities, significant sources include unvented combustion, off-gassing of building materials and furnishings, cleaning materials, and the ground below the building. Eliminating the source of the pollutants is the best way to achieve IAQ, but what can't be eliminated at the source should be extracted with exhaust fans. Dilution with fresh air should be the last method, although it is the most commonly used method for controlling IAQ at present.

Air pollution from combustion, which includes the odorless and deadly gas carbon monoxide, comes mainly from unvented kerosene and gas space heaters and attached garages. Carbon monoxide can also be generated by poorly maintained gas appliances, such as kitchen stoves, and by tobacco smoke, fireplaces, and leaky wood stoves. Any indoor combustion should be directly vented outdoors.

Off-gassing of volatile organic **compounds (VOCs)**, such as formaldehyde from plywood, particleboard, furniture, carpets, and drapes, can cause severe reactions in some people and is unhealthy for everyone. Use materials low in VOCs and vent buildings well, especially when new. If loose asbestos is present, it should be immediately removed.

Specify interior finishes and furnishing with low VOCs!

Besides specifying materials that off-gas few VOCs, specify materials that absorb and destroy VOCs. One such material is a gypsum board called AirRenew®.

Radon gas, which is radioactive, odorless, and colorless, occurs naturally in the earth, from where it slowly makes its way to the surface. In those locations where there are high concentrations, radon gas must be blocked from entering the building (see Section 15.15).

Moisture in a crawl space or basement encourages mildew growth, which is highly allergenic and sometimes toxic. Certain types of microorganisms growing in moist buildings and air-conditioning equipment produce deadly toxins like those in the fatal Legionnaire's disease. Keeping a building dry and properly maintaining the air-conditioning equipment are the best ways to control these microorganisms.

Although indoor green plants can be a source of microorganisms if overwatered, they can also act as **biofilters**, scrubbing the indoor air. The main benefit comes from microorganisms that live on the roots of plants. Because these organisms remove and destroy VOCs from the water surrounding the roots, indoor air must come into contact with the water. One effective method is the vertical hydroponic (no soil) green wall (Fig. 16.17b). As indoor air is blown through the wet green wall some of the VOCs are transferred to the water. This technique is known as phytoremediation. The creation of high indoor air quality by design and specifications will reduce the need for ventilation, which is a major energy load on a building.

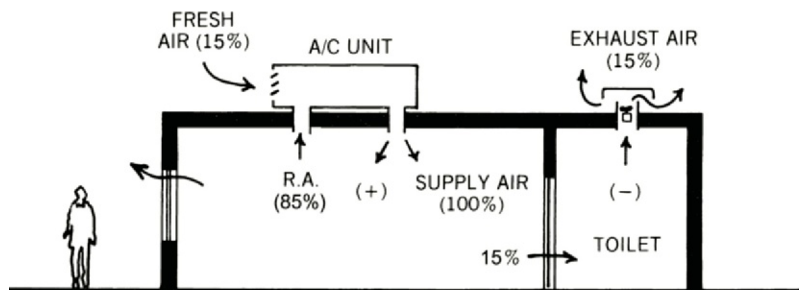


Figure 16.17a A slight positive pressure in the building prevents infiltration, and a slight negative pressure in toilets prevent odors from spreading to adjacent spaces.



Figure 16.17b An indoor vegetated (green) wall can be used as a biofilter by having the return air pass through the vegetation.

IAQ Rules

1. Avoid using toxic cleaning materials.
2. Avoid storing toxic materials indoors.
3. Avoid specifying building materials that will off-gas VOCs.
4. Use indoor materials and vegetation to remove VOCs from indoor air.
5. Avoid specifying furniture that will off-gas.
6. Avoid specifying floor and wall coverings that will off-gas.
7. Do not use unvented heaters.
8. Prevent water leaks (keep the building dry).
9. Dehumidify air if relative humidity is over 80 percent.
10. Minimize radon entry into the building.
11. Use exhaust fans where pollutants are generated.
12. Lastly, use ventilation to remove any remaining pollution.

16.18 ENERGY-EFFICIENT VENTILATION SYSTEMS

Although ventilation cannot be completely eliminated to save energy, there are several techniques available to greatly reduce the energy penalties of introducing outdoor air. If there is little or no off-gassing of toxic materials and if the buildup of carbon dioxide is the main reason for ventilation, it is possible to use **demand-controlled ventilation (DCV)**, where the amount of outside air is adjusted by carbon dioxide sensors. Thus, ventilation can be reduced but not eliminated. However, the remaining ventilation can be made much more energy efficient by using a number of techniques. Zero-energy ventilation is possible during a sunny winter day by using a solar system to preheat the outdoor air (see Section 8.24). In summer, the ventilation air can be precooled by passing it through tubes buried in the ground (see Fig. 10.14d) or by a specifically designed crawl space labyrinth (see Fig. 8.24c). When these techniques are not possible or are insufficient, heat recovery equipment can save most of the energy lost to ventilation at any time of day or year.

Heat Recovery Ventilators

Heat recovery ventilators, also known as **heat exchangers** or **air-to-air heat exchangers**, can capture much of the heat that is ordinarily lost during ventilation. When in winter air is exhausted from a building to make room for fresh outdoor air, a large amount of both sensible and latent heat is lost. The cold, dry outdoor air must be heated and humidified, and in summer, the outdoor air must be cooled and dehumidified. Some heat-recovery ventilators use fixed plates or heat pipes to capture only the sensible heat (Fig. 16.18a). Other ventilators are more sophisticated and recover both latent and sensible heat. The fixed plates in some heat exchangers are made of a special material that enables water vapor to move through the plates (Fig. 16.18b). Another type recovers between 70 and 90 percent of the heat by means of a heat-transfer

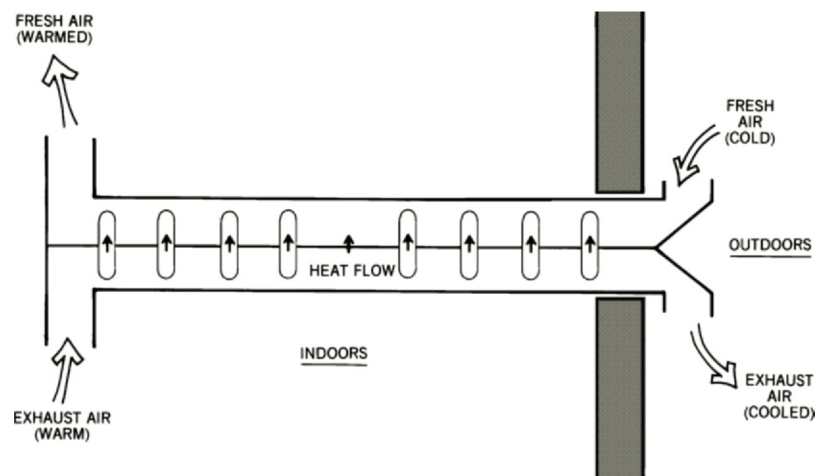


Figure 16.18a Heat-recovery ventilators allow part of the heat in exhaust air to be recovered without cross-contamination of the airstreams. Typically, the heat moves through metal partitions, but heat pipes can be used to improve the energy transfer.

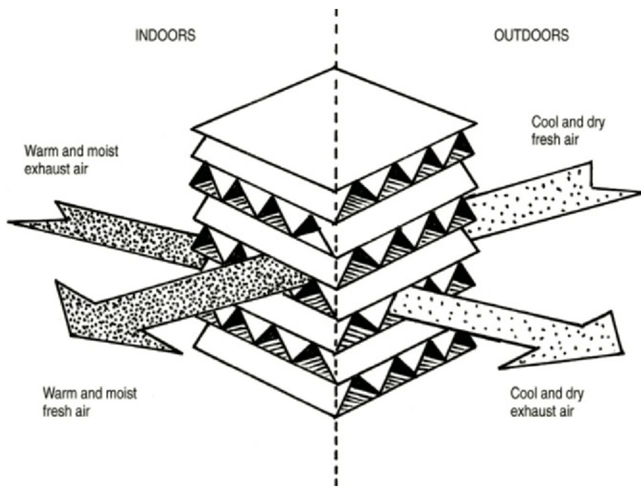


Figure 16.18b Some flat-plate heat exchangers transfer only sensible heat across metal partitions. The one shown uses composite-resin partitions to transfer latent as well as sensible heat (winter condition shown). (After Mitsubishi Electronics, HVAC Advanced Products Division.)

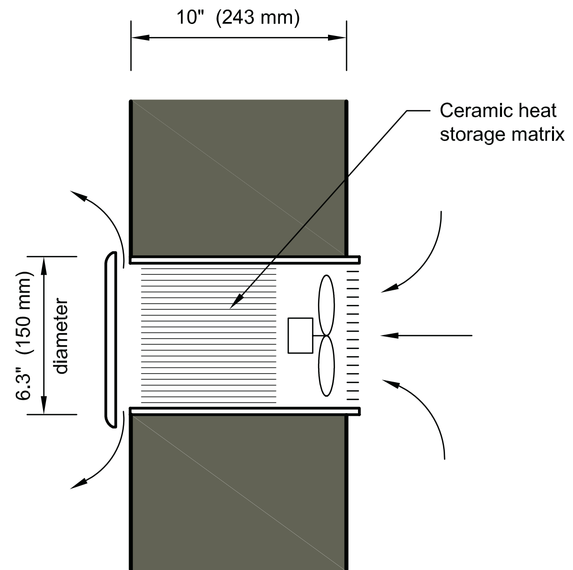


Figure 16.18d The heat recovery unit called Lunos is a short cylinder that fits into a hole cut into a wall. Each room has two units synchronized so that one exhausts while the other supplies air, and they reverse direction every minute. Their ceramic matrix first extracts heat and then releases it as the direction of airflow reverses.

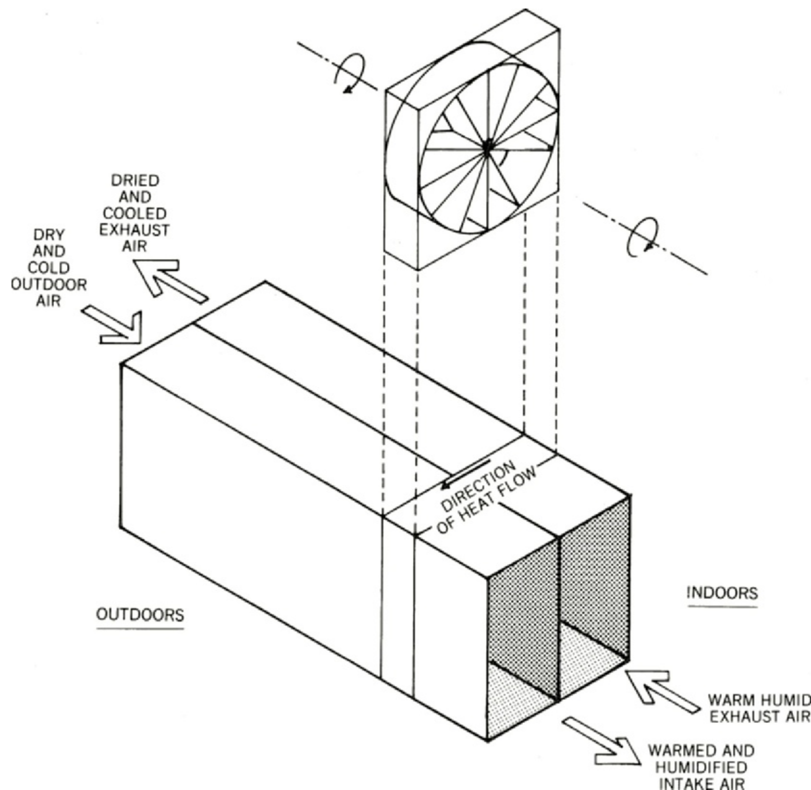


Figure 16.18c A heat-transfer wheel can recover both sensible and latent heat from exhaust air. Although the winter condition is shown, it works equally well in summer. (After *Architectural Graphic Standards*.)

wheel covered with lithium chloride, a chemical that absorbs water. As the wheel turns, both sensible and latent heat is transferred from one airstream to another (Fig. 16.18c).

A very simple heat-recovery unit called Lunos is available for individual rooms. The unit fits into a circular hole about 6.3 in. (150 mm) in diameter cut into a wall (Fig. 16.18d). A fan inside the unit blows indoor air across a heat-storing ceramic matrix for about one minute, and then the fan reverses and pulls in fresh air for a minute again through the ceramic matrix. In the winter, the outgoing air heats the matrix, which then heats the incoming air one minute later. Another unit on the opposite end of the room operates 180 degrees out-of-phase so that when one unit is exhausting air, the other unit is supplying fresh air. The main advantages of this device are low cost, no ducts, and very low energy consumption.

Displacement Ventilation

The typical method of supplying cool and fresh air to spaces is shown in the

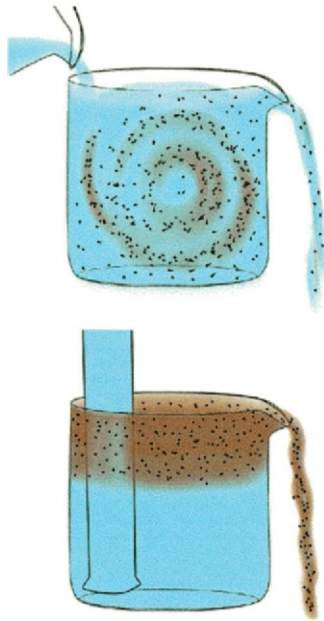


Figure 16.18e When fresh, cool water is poured into a beaker of polluted water, the resulting water is a little less dirty and cooler. However, when fresh, cool water is carefully inserted at the bottom of a beaker, much more pollution is eliminated, and the bottom layer is clean and cool. When used with air, this method is called displacement ventilation.

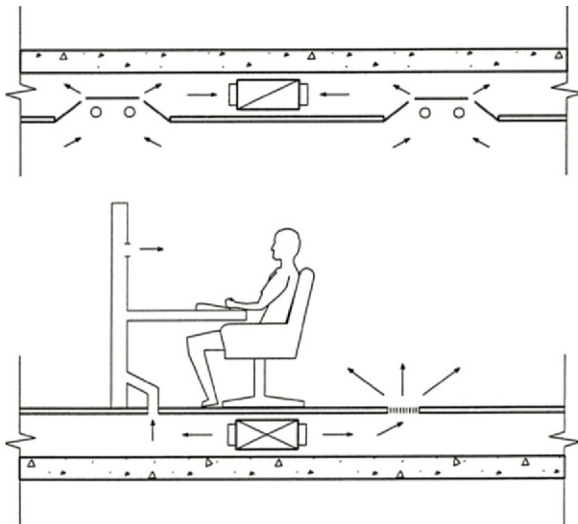


Figure 16.18f Displacement ventilation uses a raised floor to supply fresh air low in the room and sometimes directly to the occupants. The polluted warm air rises and is then exhausted at the ceiling and sometimes through the lighting fixtures. This arrangement results in exceptionally clean air and is very energy efficient.

water analogy of Figure 16.18e. The polluted, warm water in the pitcher (top) is being diluted by the addition of cool, clean water. A much more effective approach is the method used in the pitcher (bottom), where the cool, clean water is displacing the warmer polluted water. Similarly, a **displacement ventilation** system supplies fresh cool air at floor level and exhausts polluted warm air though the ceiling (Fig. 16.18f).

Compared with conventional ventilation systems, displacement ventilation creates much higher indoor air quality and smaller supply ducts. Energy is also saved because the hottest air collecting at the ceiling is removed from a space and less air needs to be moved around the building. Furthermore, supplying air under every workstation allows personal control resulting in greater occupant comfort, satisfaction, and productivity.

16.19 AIR FILTRATION AND ODOR REMOVAL

Besides heating and cooling, the mechanical system must also clean the air. The amount of dust, pollen, bacteria, and odors in air has an effect on the health and comfort of the occupants, as well as on the cleaning and redecorating costs of the building. Outdoor makeup air mixed with the return air should pass through filters first so that coils and fans can be kept free of the dirt that would reduce their efficiency. Among the many types of filters, the most popular are dry filters, electronic filters, water sprays, and carbon filters.

Dry filters are usually made of fiberglass and are thrown away when dirty. Although most dry filters remove only large dust and dirt particles, **high-efficiency particulate (HEPA)** dry filters that can remove microscopic particles such as bacteria and pollen are available. An efficient device for removing very small particles is the electronic air cleaner. Odors can be reduced by passing the air through a water spray or over activated carbon filters. The best solution for controlling odors is to prevent them, if possible, or use spot ventilation.

16.20 SPECIAL SYSTEMS

District Heating and Cooling

High efficiency is possible when a complex of buildings can be heated and cooled from a district plant. For example, on many college campuses, hot and chilled water is distributed through insulated pipes to all the buildings (Fig. 16.20a). The district plant contains large, efficient boilers, chillers, and cooling towers. Since the equipment is centralized and highly automated, a small staff can easily maintain it.

Combined Heat and Power

As first mentioned in Section 3.21, a **combined heat and power (CHP)** system can be an efficient method of supplying a building or a complex of buildings with electricity, hot water, and even chilled water. Through the generation of electricity on-site, the heat normally wasted can be used for space

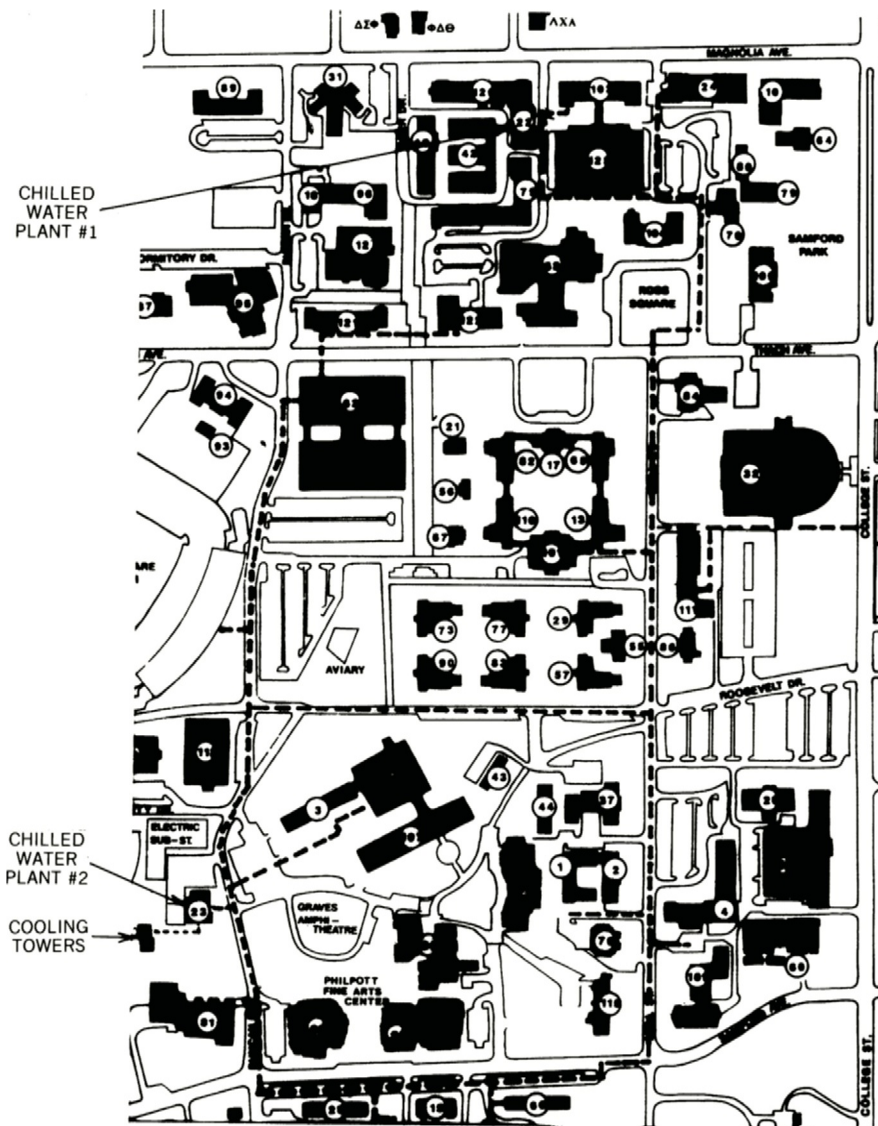


Figure 16.20a Most buildings on the Auburn University campus in Alabama are heated and cooled from central plants. Only the district cooling system is shown. As time passes, more buildings, both new and old, are added to the district system.

heating or domestic hot water. The waste heat can also be used to drive an absorption refrigeration machine to generate chilled water for summer cooling. Cogeneration can be used in installations as small as a fast-food restaurant or as large as a university campus.

With the restructuring of the electric power industry, it will be easier and more financially attractive to generate one's own electricity, with the "waste" heat being a bonus.

Thermal Energy Storage (TES)

A good strategy is to save energy from times when there is an excess for times when there is a shortage. We have seen this technique used for both passive heating and cooling where the mass of the building is usually used to store heat from day to night. Besides the heat storage of active solar hot-water systems, there are many other ways that active mechanical systems can store energy.

For example, since power companies usually have excess capacity at night, they frequently offer substantially lower rates for electricity during night hours. The power companies also have a "demand charge" for their large customers, who have to pay according to not only their energy use but also their maximum demand. One result of the smart grid is time-of-day pricing, which will make electricity very expensive for all power customers during those daylight hours when demand is greatest. Consequently, storing heat will become even more economical.

In the winter, hot water can be generated at night and stored for domestic hot water and space heating for the next day. During the summer, chilled water or ice can be produced at night for cooling the next day. Not only does the electricity cost much less, but the chillers operate much more efficiently during the cool nighttime hours. Furthermore, night energy storage can help with the problem of what to do with wind energy produced at night.

The main additional cost for active thermal storage is the water tank required for holding the hot or chilled water. If space for the chilled water tank is limited, ice can be used instead of water. Water tanks are about seven times larger than ice storage tanks. For a large office building, the size of a chilled water tank is about the same as a medium-sized swimming pool. Where open land is available, large, insulated tanks can be either partially buried or placed aboveground to become part of the architecture (Fig. 16.20b).

Some people have realized that summer heat could be stored for use in the winter. A solar collector operating at peak efficiency in the summer or a condenser coil on an air-conditioning unit could heat water for the winter. In addition, the winter cold can be used to generate chilled water or ice to be stored for the following summer, much like the nineteenth-century New Englanders who harvested ice in the winter and sold it to the South in the summer.



Figure 16.20b This aboveground thermal/water storage tank is used as an aesthetic element. (Courtesy of Chicago Bridge & Iron Company.)



Figure 16.21a Exposing the mechanical equipment can add richness and complexity to architecture. Occupational Health Center, Columbus, Indiana, by Hardy, Holzman, Pfeiffer. (Courtesy of Cummins Corporation.)

When seasonal ice is used, it should be stored in insulated tanks. When water is used, tanks tend to be too large and the water in the ground should be used. Waterproof liners and rigid insulation can isolate a section of earth with its groundwater. This concept is known as an **annual-cycle energy system (ACES)**. The geo-exchange, ground-coupled heat pumps described in Section 16.11 use this concept to a limited extent.

16.21 INTEGRATED AND EXPOSED MECHANICAL EQUIPMENT

Usually, mechanical equipment is a completely separate system hidden behind walls and above suspended ceilings. Perhaps it is time for the equipment to come out of the closet. This can happen either by integrating the mechanical equipment with other building systems, such as the structure, or by exposing the equipment to full view. Many successful buildings illustrate both approaches.

Instead of separate systems, the integrated approach tries to make each construction element do as many jobs as possible. As Buckminster Fuller urged, "do more with less." Often there is synergy from the integration. For example, using the structure as ducts or plenums allows easy nighttime cooling of the structural mass to create a heat sink the next day. Although the integrated approach promises great efficiency and cost reduction, it is a more sophisticated and difficult way to design and build. It requires much more cooperation among the various building professionals than does the existing approach of separate systems.

An example of the integrated approach is the Emerald People's Utility District Headquarters near Eugene, Oregon, where the structure is used to help cool and heat the building. To increase the effectiveness of night-flush cooling, outdoor air is blown through hollow-core concrete planks, preparing them to be good heat sinks for the following summer day (see Figs. 10.9d and 10.9e). On winter mornings, indoor air is circulated through the hollow planks to more quickly extract some of the heat stored in them from the previous day. Also, the second-floor main ducts prevent direct glare from the clerestory windows.

The most dramatic way to recognize the mechanical equipment as a legitimate part of architecture is to expose it to view. Especially at a time when a more ornate and colorful style is replacing the simplicity and clean lines of modern architecture, the exposed mechanical equipment can add complexity and richness to a building.

An example of this approach is the Occupational Health Center in Columbus, Indiana, where all the pipes and ducts are exposed to view (Fig. 16.21a). Bright colors define and clarify the various systems of supply air, return air, hot-water heating, etc.

Since exposed ducts must be made of better material and require higher-quality work, they cost more than conventional equipment. This higher cost can be offset by savings from the elimination of a suspended-ceiling system.

At the Centre Pompidou, in Paris, architects Richard Rogers and Renzo Piano exposed the mechanical equipment not only on the interior but also on the exterior (Fig. 16.21b).



Figure 16.21b The Centre Pompidou, Paris, France, by Richard Rogers and Renzo Piano. Much of the mechanical equipment is exposed on the exterior of the building, outside the building envelope. Biomimicry would suggest, however, that it is not a good idea to expose the guts outside a protective skin. (Photograph by Clark Lundell.)

Any heat gain or loss to the ducts and pipes exposed on the interior is either helpful or not very harmful. For example, in the winter, any heat lost from ducts on pipes will help heat the interior. This is definitely not the case with exterior ducts or pipes, which are exposed to the harsh climate. It is worthwhile to note that in nature no creatures have their guts on the outside of their skin. Such creatures might be born, but they do not survive. The Centre Pompidou might be a great monument, but it should not be considered a widely applicable prototype; for future buildings, the mechanical equipment should remain inside of the building skin. Furthermore, as was explained in the previous chapter, all heat bridges through the thermal envelope should be minimized. Exposing a building's structure on the exterior is not sustainable, just as having the guts outside the skin is not sustainable for animals.

SIDEBOX 16.22

The efficiency of HVAC equipment is rated by the following measurement instruments:

Coefficient of Performance (COP) is a measure of the usable energy output divided by the energy input. It is frequently used to rate heat pumps.

Energy Efficiency Ratio (EER) is a measure of the cooling capacity (i.e., maximum output possible) divided by the energy input. It is often used to rate residential air conditioners.

Seasonal Energy Efficiency Ratio (SEER) is a measure of the total cooling output (actual output) during the whole overheated period divided by the total energy input during that same period. It is often used to rate residential air conditioners.

Integrated-Part-Load Values (IPLV) is a measure of the efficiency of multi-split systems operating in part-load conditions. COP and EER measure the efficiency of equipment operating at full capacity even though that is not typical of most applications. IPLV been replaced by IEER (see below).

Annual Fuel Utilization Efficiency (AFUE) is a measure of the annual heat output divided by the annual energy input in regard to boilers.

Heating Season Performance Factor (HSPF) is a measure of the efficiency of air-source heat pumps.

Integrated Energy Efficiency Ratio (IEER) is a measure of the part load efficiency of multi-split systems and it was previously known as IPLV.

16.22 LOW ENERGY HEATING AND COOLING

In most small buildings and in many large buildings, the most energy is used for heating and cooling. To minimize the energy consumption of the HVAC equipment, do the following:

1. Design the building itself so that it needs very little heating and cooling (e.g., orientation, form, passive heating and cooling, shading, a great thermal envelope, etc.).
2. Use geo-exchange (geothermal) heat pumps.
3. Use air-to-air heat pumps.
4. Use an air system only for ventilation.
5. Use water or refrigerant rather than air to heat and cool a building.
6. Use chilled beams where appropriate.
7. Use radiant floor heating where appropriate.
8. Use large diameter, short length, and straight run ducts.
9. All ductwork must be on the indoor side of the thermal envelope!
10. Use heat recovery ventilators (heat exchangers).
11. Use displacement ventilation where appropriate.
12. Consider combined heat and power systems.
13. Consider thermal storage systems to shift load from day to night.

See Sidebox 16.22 for rating systems of HVAC equipment.

16.23 CONCLUSION

It may be surprising that it is mainly the architect who accomplishes the heating and cooling of buildings, through the decisions made in tiers one and two of the three-tier approach to sustainable design (Fig. 16.1). He or she determines not only the size but even to some extent the design of the HVAC system. The mechanical engineer's design has to meet the heating and cooling still needed after the building fabric does its work. It's almost possible for the architect to put the mechanical engineer out of business. For example, a superinsulated building will need no heating system in many cold climates, and a well-shaded passively cooled building will need neither an air-conditioning nor a heating system in some hot and dry climates.

When the design of the building itself addresses heating, cooling, and lighting, the mechanical and electrical loads can be reduced as much as 80 percent. Even the remaining 20 percent can be further reduced when the architect works with the engineers. For example, short, straight, and large ducts require much less fan power than their opposites.

Now that society realizes the importance of sustainability, it is vital that we also recognize the responsibility and the opportunity for architects to reduce the energy appetite of buildings. No professionals other than politicians have as great an impact on the environment as architects.

KEY IDEAS OF CHAPTER 16

1. Mechanical heating should supply only the small amount of heat still needed after a tight thermal envelope (tier one) and passive solar energy (tier two) have been fully utilized.
2. Fireplaces are highly inefficient unless they have a heat exchanger, outdoor combustion air, and doors. Stoves are much more efficient than even the best fireplaces.
3. All but the smallest buildings have more than one thermal zone.
4. The number of required zones has a great impact on the choice of a mechanical system.
5. Heating systems
   a. Hot-water (hydronic) systems are efficient and comfortable but generally are not useful for cooling.
   b. Hot-air systems are appropriate when cooling is also required.
   c. Electric-resistance heating should be used as little as possible because it is most wasteful of energy.
   d. Heat pumps are an efficient way to heat and cool with electricity. Geothermal (geo-exchange) heat pumps are more efficient than air-to-air heat pumps.
   e. Combined heat and power (CHP) systems can supply heat at low cost.
6. Mechanical cooling should supply only the small amount of cooling still required after all the heat avoidance (tier one) and passive cooling (tier two) techniques have been employed.
7. Cooling systems use refrigeration machines to pump heat from lower temperatures indoors to higher temperatures outdoors.
8. Although the compression refrigeration cycle is more efficient than the absorption refrigeration cycle, an inexpensive source of heat can make the absorption cycle attractive.
9. In the compression cycle, the refrigerant moves heat from the evaporator coil to the condenser coil.
10. Air-to-air and geothermal (geo-exchange) heat pumps can cool as well as heat. Four energy sources/sinks are possible: ponds, well water, vertical ground loops, and horizontal ground loops.
11. Chillers produce chilled water that is used in air-handling units and fan-coil units.
12. Large quantities of heat are efficiently dumped into the atmosphere by evaporative coolers and cooling towers.
13. Packaged units allow a maximum of mechanical fabrication to be performed in the factory.
14. Split systems are, in effect, two packaged systems.
15. Internal duct insulation, sound traps, and sections of flexible ducts control mechanical noise and vibration.
16. Variable-air-volume (VAV) systems are efficient but are limited to either heating or cooling a building at any one time.
17. Fan-coil systems provide many zones at modest cost, but they provide fresh air only if they are located on an outside wall.
18. Ductless split systems come in three types: mini-split, multi-split, and multi-split with variable refrigerant flow (VRF).
19. Mechanical equipment rooms (MERs) should be centrally located to minimize the quantity and complexity of the ductwork.
20. Round ducts are most efficient, but oblong and rectangular ducts require less headroom. Flat oval ducts are a compromise.
21. Diffusers and registers mix supply air and room air without causing drafts. Both have dampers to control the volume of air. Grilles might or might not direct the flow of air, and they do not contain dampers.
22. Indoor-air quality (IAQ) is a high priority for health and productivity. Clean, healthy air is achieved by:
   a. Eliminating sources of pollution (e.g. volatile organic compounds [VOCs]).
   b. Directly exhausting the source of pollutants.
   c. Using ventilation to dilute pollutants.
   d. Using living plants to clean air.
23. Heat-recovery units are excellent devices for minimizing heat loss from ventilation. Both sensible and latent heat can be recovered from these air-to-air heat exchangers.
24. Displacement ventilation is more efficient than conventional ventilation in eliminating pollutants.
25. The economizer cycle uses cold outdoor air when available to cool a building.
26. Combined heat and power (CHP) systems, formerly known as cogeneration systems, can be more efficient than buying electricity and heating energy separately.
27. District heating and cooling systems are more efficient than smaller individual systems.
28. Thermal-storage systems can take advantage of low night electricity rates and the greater efficiency of running refrigeration machines in cool night air. The energy storage (heat sink) can be in the form of chilled water, ice, or the mass of the building itself.
29. Exposing mechanical equipment and ducts on the interior is efficient and has aesthetic potential. Exposing ducts and pipes on the outdoor side of the thermal envelope is very inefficient and not sustainable. Ducts, pipes, and the structure should always be located inside the thermal envelope.

Resources

Further Reading

(See the Bibliography in the back of the book for full citations.)

Allen, E. *How Buildings Work: The Natural Order of Architecture*, 2nd ed.

Allen, E., and J. Iano. *The Architect's Studio Companion: Technical Guidelines for Preliminary Design*, 3rd ed.

ASHRAE. *Air-Conditioning Systems Design Manual*.

———. *Terminology of Heating, Ventilation, Air Conditioning, and Refrigeration*, 2nd ed.

Bachmann, L. *Integrated Buildings: The Systems Basis of Architecture*.

Baird, G. *The Architectural Expression of Environmental Control Systems*.

Banham, R. *The Architecture of the Well-Tempered Environment*, 2nd ed.

Bearg, D. W. *Indoor Air Quality and HVAC Systems*.

Bobenhausen, W. *Simplified Design of HVAC Systems*.

Bradshaw, V. *Building Control Systems*, 3rd ed.

Brown, G. Z., and Mary DeKay. *Sun, Wind, and Light: Architectural Design Strategies*, 3rd ed.

Cox, S. *Losing Our Cool: Uncomfortable Truths about Our Air-Conditioned World (and Finding New Ways to Get through the Summer)*.

Egan, M. D. *Concepts in Thermal Comfort*.

Flynn, J. E. *Architectural Interior Systems: Lighting, Acoustics, Air Conditioning*, 3rd ed.

Grondzik, W., and A. G. Kwok. *Mechanical and Electrical Equipment for Buildings*, 12th ed.

Grumman, D. L., ed. *ASHRAE Green Guide*.

Guise, D. *Design and Technology in Architecture*.

Knight, P. A. Mechanical *Systems Retrofit Manual: A Guide for Residential Design*.

Lang, P. V. *Principles of Air Conditioning*.

Lyle, D. *The Book of Masonry Stoves: Rediscovering an Old Way of Warming*.

Reid, E. *Understanding Buildings: A Multidisciplinary Approach*.

Rush, R. D., ed. *The Building Systems Integration Handbook*.

Trost, J. *Heating, Ventilating, and Air Conditioning*.

Wright, L. *Homefires Burning: The History of Domestic Heating and Cooking*.

Organizations

(See Appendix K for full citations.)

American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE)
www.ashrae.org

GeoExchange
www.geoexchange.org

Radiant Professional Alliance
www.radiantprofessionalsalliance.org

CHAPTER 17

TROPICAL ARCHITECTURE

Do unto those downstream as you would have those upstream do unto you.
Wendell Berry

17.1 INTRODUCTION

The part of the world that lies between the Tropic of Cancer (23.5°N latitude) and the Tropic of Capricorn (23.5°S latitude) is called the tropics, and it contains much of the earth's landmass. In the Americas, the tropics extend from the middle of Mexico to the southern part of Brazil. Most of Africa, half of India, all of Southeast Asia, and all of Indonesia fall in the tropics (Fig. 17.1).

The tropics will see much of the world's future construction because it contains many quickly developing countries. Furthermore, its already large population will continue to grow rapidly, from the present 40 percent to about 60 percent of the world's population by 2060. These trends will result in much work for architects and builders but will also present a great challenge for the sustainability of the planet.

This chapter will explain how to design buildings in the tropics that are cooled and lit as sustainably as possible. Since the design of buildings in the tropics is similar to those designed in very hot regions of the temperate zones, this chapter only discusses how they differ. For those aspects where the design is the same, the reader is referred to the appropriate chapters elsewhere in the book. Consequently, anyone designing buildings in the tropics should study all of the chapters in this book except for Chapter 7, which covers passive solar heating. Especially relevant are Chapters 6, 9, and 10.

17.2 TRADITIONAL TROPICAL ARCHITECTURE

To be low energy, modern buildings must borrow as many strategies as possible from traditional buildings that were properly designed for their climate. Because of cultural, climate, and sun angle differences, traditional tropical buildings come in a great variety. The degree of comfort that they can provide also varies greatly, with greater indoor comfort possible in hot and dry than in hot and humid climates. Because the resulting designs are so different, hot and dry climates will be discussed separately from hot and humid.

Hot and Dry Climates

Although daytime temperatures are much higher in dry than humid climates, the high diurnal temperature range of dry climates can create comfort by the use of massive walls and roof structures. The time lag of the resulting large thermal mass, combined with night-flush cooling, can create indoor comfortable temperatures most of the year and most of each day (see especially Section 10.9).

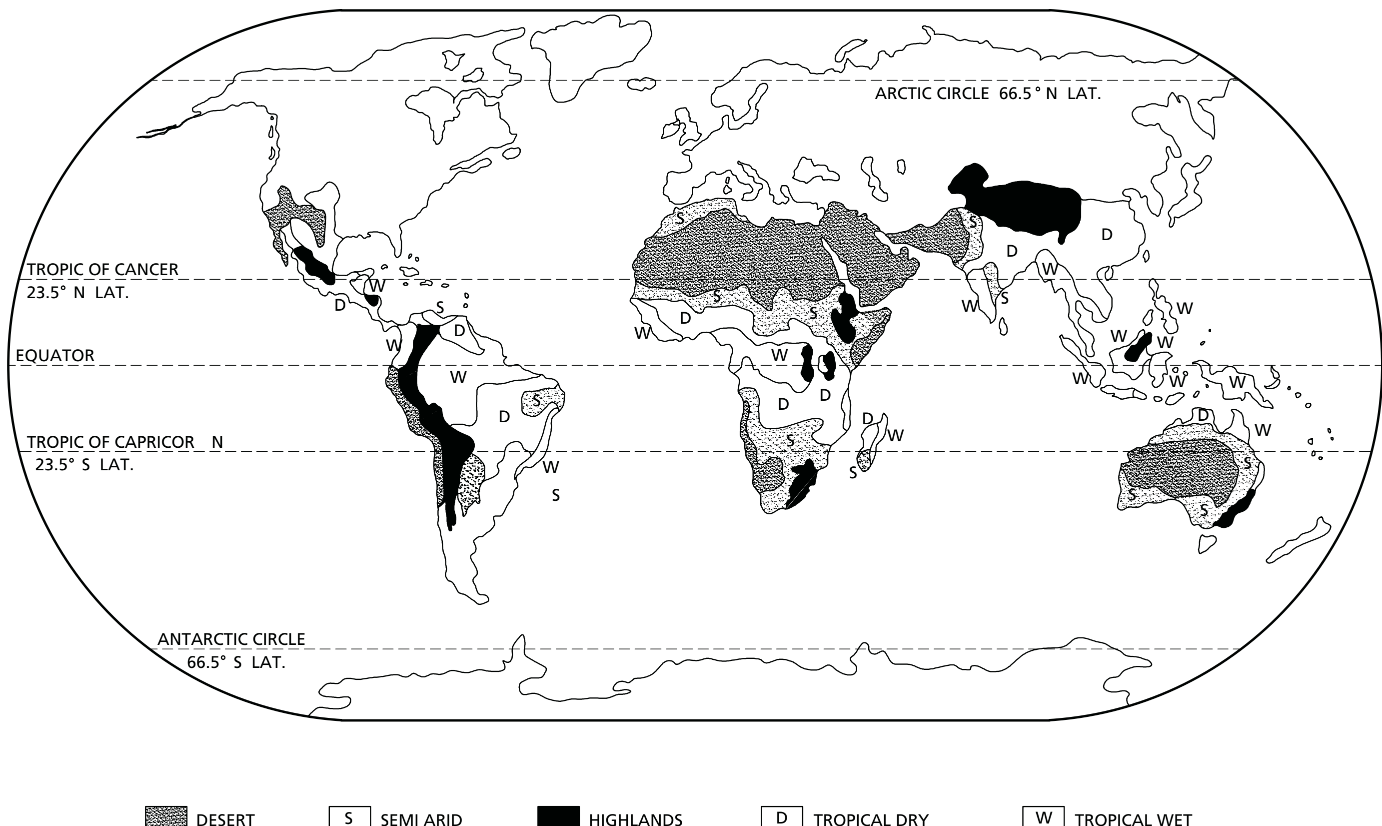


Figure 17.1 The land area of the tropics is about equally divided between dry and wet climates. Most people, however, inhabit the wet regions because more food can be grown there.

However, the benefits of thermal mass in hot and dry climates can be negated if too much sun is allowed to enter during the day. Thus, because keeping the sun out is critical, a common shading strategy was to have small windows facing a narrow street or alley (Fig. 17.2a). When windows were not shaded by neighboring buildings or when large windows were desired, various shading devices were used. The most common of these were louvered shutters that kept most of the sun out while allowing a small amount of daytime ventilation (see far left in Fig. 17.2b). The shutters would then be opened for night-flush cooling. Also quite common were overhangs which would work well on south facades (north in the Southern Hemisphere), but on east and west facades additional vertical shading devices such as shutters or outdoor curtains were required to keep out the low morning and afternoon sun. Outdoor curtains were popular on east and west windows because they, like shutters, could be left open half of the daytime hours and all of the night to again maximize night-flush cooling (Fig. 17.2b). Evaporative cooling by means of hanging wet blankets in the path of incoming air was also used in some regions.

Multistory buildings with small but deep courtyards were very popular and appropriate in hot and dry climates (see Fig. 10.2g). Most if not all windows faced the courtyard, which is self-shaded much of the day. Because cool air sinks and because the bottom floor is most shaded, the family spent much of the summer there. In the winter, the top floor was most comfortable, because it gets the most sun and warm air rises. When possible, ceilings were high to benefit from stratification. The outdoor walls were usually of a light color to reflect the sun.

Shading was not limited only to buildings. Market streets often had either overhead shading if they were narrow or colonnades or arcades if they were wide. If these covered sidewalks were on north–south streets, their exposure to the east or west was frequently protected by movable vertical shading (Fig. 17.2c).



Figure 17.2a This narrow alley in the old section of Fez, Morocco, provides much shade for the windows, walls, and the alley itself. The white walls further reduce solar heat gain.



Figure 17.2b In hot climates, shade is the top priority for achieving thermal comfort. This street scene in modern Fez, Morocco, shows many of the strategies used: louvered shutters (far left), a small overhang (window in center), covered balconies, and outdoor curtains.



Figure 17.2c Arcades and colonnades are popular in hot climates to shade both storefronts and pedestrians. Although this colonnade in Casablanca, Morocco, is quite wide, it nevertheless uses outdoor roller shades to protect from the low morning or late afternoon sun because it is on a north–south street.

Hot and Humid Climates

Although the daytime temperatures are much lower in humid climates than in dry climates, when combined with the high humidity, they create great discomfort. The high humidity makes it very hard for the body to cool itself through sweating. The low diurnal range results in nighttime temperatures that are still too high for thermal mass to be helpful. The only strategies available in hot and humid climates are heat avoidance and maximizing natural ventilation both during the day and at night.

Traditionally, heat avoidance was primarily achieved by shading, as can be seen in Figure 17.2d. Thus shading is a critical strategy in all hot climates. Shading is achieved mostly by large roof overhangs, porches, and shutters (Fig. 17.2e). On east and west facades, vertical shading was required in addition to overhangs, and it was usually accomplished by shutters or bamboo roll-up shades (Fig. 17.2f). Heat was also avoided by using low light levels and by cooking outdoors.

Even when the indoor temperature was minimized by heat avoidance, it was still too warm for comfort because of the high humidity. However, thermal comfort could be achieved or at least approached by moving air across human bodies by means of natural ventilation. A building with no walls would be ideal, but privacy and security usually require a barrier, such as the very open screens seen in Figures 17.2g and 17.2h. Raising the building on stilts increases natural ventilation because wind speeds increase with height. Buildings on stilts also provide security against people and animals, since the walls are often nothing more than an open weave punctured with windows. In urban areas with a high cost of land, buildings tend to be higher and can therefore experience more natural ventilation. Traditionally, one common strategy was to place monitors on the roof to exhaust hot air by means of both a negative pressure caused by the wind and the stack effect (Fig. 17.2i).



Figure 17.2d Shade is the number-one priority in hot climates, as these motorcyclists in a very hot and humid part of China demonstrate.



Figure 17.2e This traditional Indonesian house demonstrates many of the strategies appropriate in hot and humid climates. The house is raised on stilts both to get above the humidity and surface water on the ground and to raise the building to catch more wind. The high roof allows for stratification and good gable ventilation. The large covered porch provides shading for windows, walls, and an outdoor living space. To maximize natural ventilation, the windows are floor to ceiling and protected by louvered shutters.

Ceilings would be high or nonexistent for the benefit of stratification. In one-story buildings or the top floor of multistory buildings, there would be no ceiling. Since roofs are typically steep gables, these spaces would be very high and well ventilated all the way to the ridge, thereby exhausting the hottest air, which collects there.



Figure 17.2f The low east and west sun make shading those orientations very difficult but especially necessary. A common solution was to have deep covered porches with roll-down bamboo curtains.



Figure 17.2h This traditional upper-class home in Malaysia maximizes natural ventilation while providing significant security through carved screens and windows with shutters. Note how the roof seems to float on the walls to further maximize natural ventilation.



Figure 17.2g To maximize natural ventilation, this Southeast Asian rustic home has walls that are as porous as possible while still providing some security and privacy. Also note the gable vents that also allow light to enter.

Windows needed to be large to maximize natural ventilation. Louvered shutters were popular because they allowed much nighttime ventilation and some daytime ventilation while keeping the sun out. Since daytime ventilation will heat the indoors while cooling people by evaporation, thermal mass is not desired. It would only store heat during the day to make it even hotter at night. Furthermore, it is not cool enough at night to cool the mass sufficiently for it to be a heat sink the next day. Instead, traditional buildings in hot and humid climates were made of lightweight materials such as wood. Even palaces were made of wood (Fig. 17.2j), which was perforated with carved screens in both the outdoor walls and indoor partitions.

Before air-conditioning became available, the above strategies were used from the lowliest structure to the most expensive buildings of the rich and noble. Although not ideal in hot and humid climates, masonry walls were sometimes used either to protect against fire, especially in urban areas, or for protection against storms and human enemies. This was especially true of buildings constructed by the colonial powers. These buildings were usually a blend of the type used in the home country of the imperial power and the local strategies more suited to the climate (Figs. 17.2k and 17.2l).

Traditional site planning and landscaping also contributes to thermal comfort. When possible, buildings in the hot and humid tropics were sited to maximize access to the wind. When courtyards were used, they were open to the wind either by having the building on stilts or by maintaining breezeways between the four buildings that formed the courtyard. The landscape would consist of mostly tall trees because they provide shade without blocking the wind near ground level.



Figure 17.2i In the traditional urban Chinese building in hot and humid areas, the first floor was commercial and the second floor was residential. To maximize natural ventilation, the commercial activity was completely open to the street during the day, with awnings providing additional shade. Upstairs, large windows with louvered shutters allowed much natural ventilation at night and some during the day. The ventilation is greatly improved by the roof monitors, which operate through a combination of the stack effect, the Bernoulli effect, and the venturi effect (see Section 10.5 for an explanation of these).



Figure 17.2k The design of this European-style building in Bangkok, Thailand, adjusted as much as possible to a climate alien to its origins by means of the extensive use of large windows protected by louvered shutters. Transplanting building styles that are appropriate for one climate to an alien and inappropriate climate is a phenomenon that runs throughout the history of architecture. Unfortunately, only in some cases are the styles modified either immediately or over time to fit the new climate. For example, Auburn University in the hot South is built in the English Georgian style more suitable for a mild cloudy climate.



Figure 17.2j Lack of money was not the reason this royal palace in Bangkok, Thailand, was made of wood. Rather, it was the recognition that massive materials like stone and brick were inappropriate for promoting thermal comfort in a hot and humid climate. An abundance of beautiful carved wood screens under each window maximize ventilation.



Figure 17.2l The Raffles Hotel in Singapore is an example of a European colonial building very well adapted to the local hot and humid climate. Not only are all of the rooms protected by exterior corridors, but also the low sun is blocked by louvered screens.

The typical dress in each type of climate suggests some basic logic for designing appropriate buildings. In hot and dry climates, people are typically completely covered by clothing to protect against the sun. Of course, white garments are best. Nevertheless, in some very hot and dry climates, men wear white while women wear black. My suggestion for such places is for a switch so that the men wear black and women white. It would be interesting to see if the men would then conclude that both sexes should wear white. Quite differently, in hot and humid climates, people tend to wear very little clothing so that evaporative cooling is maximized. Although shading the skin is still beneficial, humid climates usually have lots of shade trees, which is not the case in dry climates, where shading the skin is more important than maximizing evaporative cooling. However, in any hot climate the clothing is very loose to help with evaporative cooling.

Since all of the above strategies can also be found in hot temperate climates, it is important to understand what is different about the tropical climates.

17.3 THE TROPICAL CLIMATE

As mentioned in Chapter 5, the word "climate" comes from the ancient Greek word for "incline." The Greeks understood that the climate of a region is very much influenced by the angle of sunrays throughout the year. In general, the higher the incline of sunrays, the warmer the climate.

A major difference between temperate and tropical climates is that it almost never gets cold enough to require heating systems in the tropics. The main exceptions are high elevations on the equator, like the Andes in Ecuador. Africa's Mount Kilimanjaro, with its year-round snowcap, is another famous example, especially since it is only 3° south of the equator. It is important to realize that it is not hotter in the tropics than it is in some temperate climates during the summer. The tropics are hotter in duration rather than in degree. In some tropical climates the temperature is almost constantly hot or very warm throughout the year, while in others it varies from hot to warm but almost never from hot to cold.

The tropical climate is often assumed to be mostly hot and humid, but the tropics also contain deserts. One of the main differences in the various tropical climates is the amount and timing of rainfall. In places such as northern Africa, rainfall is so scarce that deserts have formed (Figure 17.1). In other places, it is dry most of the year, but there is a short rainy season. For example, in some parts of India, more than 90 percent of the rain falls during the monsoon season, which occurs from June to September. And, of course, there are the lush regions of the tropics where rainfall is plentiful all year. Just as there are large variations in tropical climates, there will be large variations in the design of tropical buildings.

In dry climates, the sky is mostly clear with occasional clouds. Consequently, most solar heating comes from direct solar radiation. However, there is also a significant reflected component from the mostly bare surrounding land and structures. The sky is clear unless there is haze caused by dust raised by strong winds. The relative humidity is usually below 20 percent during the day when it has the main impact on thermal comfort. Although the relative humidity rises when air is cooled, thermal comfort does not decline, because it is a function of the simultaneous effect of temperature and relative humidity. Temperatures during a typical day tend to vary from 75° to 115°F (24° to 46°C), which gives a large diurnal range of about 40°F (22°C).

In humid climates, the sky is mostly hazy from the humidity, and clouds can be plentiful. Consequently, direct solar radiation is weaker, but the solar heating load is still very large because of the greatly increased diffuse component from the bright hazy sky. Consequently, some light from the sky must be shaded along with the direct solar radiation. Because the ground surface tends to be covered by plants, the reflected solar load is small. The relative humidity, when combined with the simultaneous air temperature, creates conditions outside the comfort zone. Temperatures during a typical day tend to vary between 80° and 95°F (26° and 35°C), which results in a small diurnal range of about 15°F (9°C).

The actual local microclimate, however, can vary greatly from the above depending on latitude, time of year, proximity to water, elevation, and local weather patterns. Latitude was mentioned first because sun angles have a great impact on the design of a building.

17.4 THE SOLAR GEOMETRY OF THE TROPICS

At the equator, the sun is directly overhead at 12 noon on both March 21 and September 21 (Fig. 17.4a). Moving north on the planet from the equator,

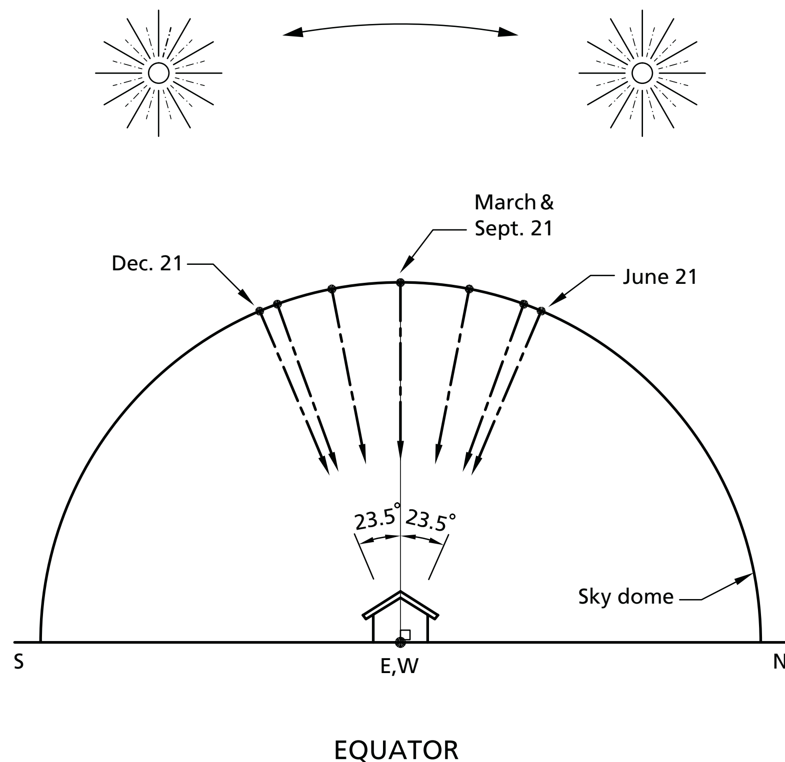


Figure 17.4a This north–south section of the skydome shows that at the equator, the sun is lowest in the sky on December 21 and June 21 and highest and directly overhead at 12 noon on the equinoxes (March 21 and September 21).

the sun continues passing overhead twice each year until one reaches the Tropic of Cancer (23.5°N latitude), where the sun is overhead only once each year on June 21 (Fig. 17.4b). Moving farther north, the sun is never overhead and gets progressively lower in the sky. The same pattern exists in the Southern Hemisphere, except that the last place the sun is ever directly overhead is the Tropic of Capricorn (23.5°S latitude) on December 21 (Fig. 17.4c). Thus, only in the tropics is the sun ever directly overhead.

At the equator, the sun shines for half the year from the south and for the other half of the year from the north. Consequently, south and north facades experience the same sun angles but at different times of the year. Since summer results from high sun angles and winter from low sun angles, the equator experiences two "summers" (sun directly overhead) and two "winters" (i.e., slightly less hot periods) when the sun is 23.5° lower in the sky (Fig. 17.4a). The existence of two summers creates not only high temperatures but also a more uniform temperature throughout the year, since it takes time to heat up and cool down (i.e., time lag) the great mass of the earth's surface. Temperatures are also quite constant at the equator because every single day of the year has twelve hours of daytime and twelve hours of nighttime. Of course, temperatures become less uniform as one moves away from the equator toward the tropics of Cancer and Capricorn, where tropical and temperate climates meet. Daily and annual temperature ranges are also affected by the presence of large bodies of water, which further dampen temperature changes.

Because heating is mostly not required, solar design in the tropics focuses only on shading and daylighting. Since the sun rises in the eastern sky and sets in the western sky everywhere on the planet, east

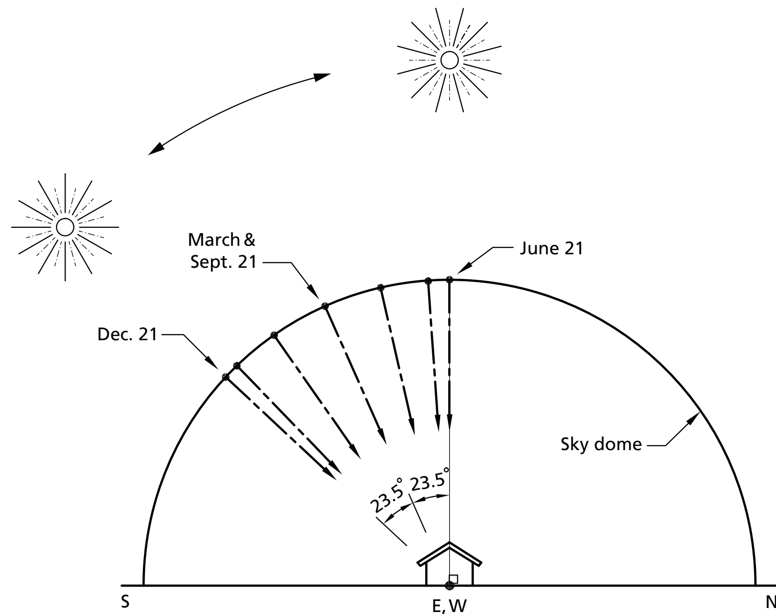


Figure 17.4b At the Tropic of Cancer, the sun is highest in the sky and directly overhead only on June 21 at 12 noon. The Tropic of Cancer is the latitude line where the tropics end and the temperate zone starts in the Northern Hemisphere.

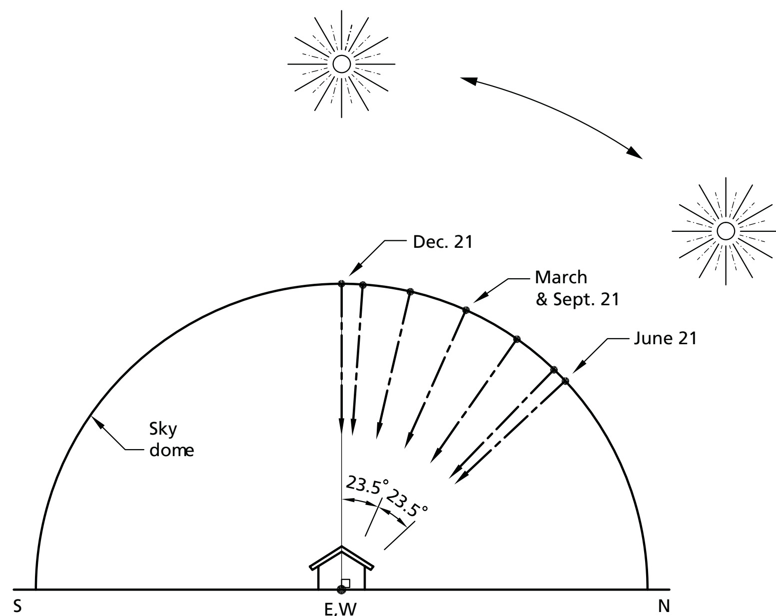


Figure 17.4c At the Tropic of Capricorn, the sun is highest in the sky and directly overhead only on December 21 at 12 noon (summer in the Southern Hemisphere). The Tropic of Capricorn is the latitude line where the tropics end and the temperate zone starts in the Southern Hemisphere.



Figure 17.4d This building in Singapore seems to have gotten everything right: long axis running east–west, narrow rectangle to maximize daylighting, and exterior shading on the long facade. But what about the other long facade?



Figure 17.4e The other long facade of the building shown in Figure 174.d looks as if it were the northern facade of a building in the northern temperate zone. However, Singapore is practically on the equator, so north and south facades should be the same.

and west windows are a problem everywhere on the planet. In the tropics, east and west windows are not just a seasonal problem; they are a problem every day of the year. Thus, the discussion in Chapter 9 in regard to minimizing east and west windows in temperate climates applies even more in the tropics. However, the north and south facades in the tropics experience significantly different sun angles than they do in temperate climates. For example, in the Northern Hemisphere, as one moves south toward the equator the sun shines increasingly into north windows until, at the equator, the north facade gets just as much sun at the same sun angles as the south facade. The two facades can therefore be symmetrical in design. Then, moving south of the equator, the north facade sees increasingly more sunlight than the south facade.

The importance of understanding solar geometry in the tropics is illustrated by the building shown in Figures 17.4d and 17.4e. This building in Singapore at 1 °N latitude looks like it was designed for a temperate climate. The long axis running east–west is correct, as is the exterior shading on one long side. However, at the equator the north and south facades should look the same.

Besides the geometry of sunbeams, it is also important to understand the amount of solar radiation falling on each face of a building. Figure 17.4f shows the intensity of solar radiation at 16 °N latitude on the four walls of a building aligned with the cardinal directions of the compass for both June 21 and December 21.

At 16 °N latitude, the south wall receives direct solar radiation on December 21 but not on June 21, while the north wall receives direct radiation on June 21 but not December 21. The direct solar radiation on the north wall is about one-third of that on the south wall. Heading south from that parallel, the solar radiation will increase on

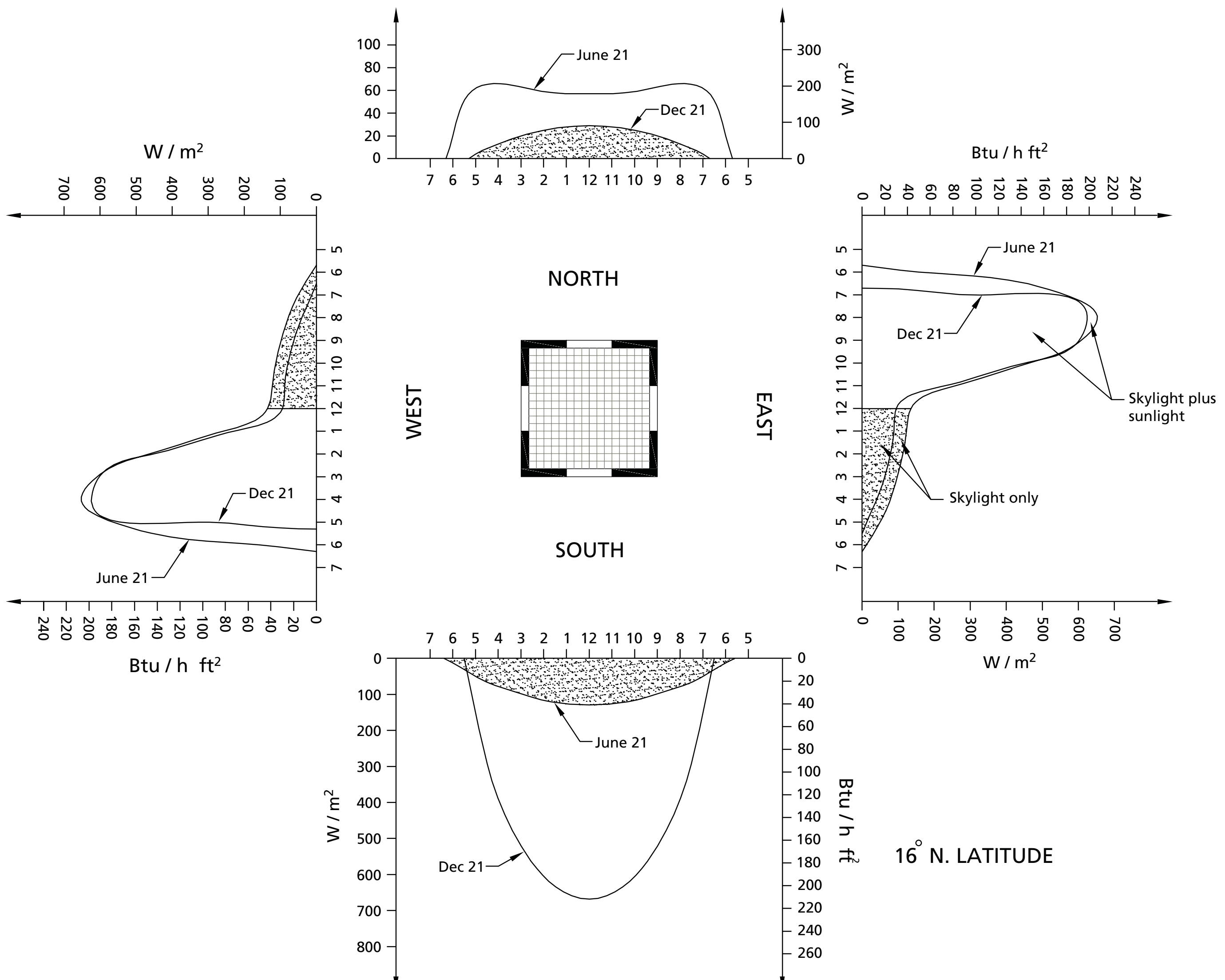


Figure 17.4f The four graphs show the solar intensity on the four facades of a building oriented along the cardinal directions of the compass at 16°N latitude. Each graph has a curve for December 21 and a curve for June 21. Note that on June 21 the south facade needs less shading than the north facade. Also note that there is almost no difference on the east and west facades all year long.

the north wall and decrease on the south wall until they are equal at the equator.

East and west walls receive the same amount of solar radiation unless local conditions such as a large building immediately to the east or afternoon rains modify the symmetry. Unlike in the northern temperate zones, the solar radiation is almost the same on June 21 and December 21. In effect, the solar load is about the same on east and west windows every day of the year.

A skylight receives almost as much solar radiation on December 21 as on June 21 (Fig. 17.4g), and at the equator the solar radiation is the same on December 21 and June 21. Thus, in the tropics skylights deliver almost constant daylighting for all days of the year, but of course it is not constant during daylight hours. Because high light levels are available about three hours before and after noon, a skylight should be designed to block much of the light around the noon hours and collect more light in the early morning and late afternoon.

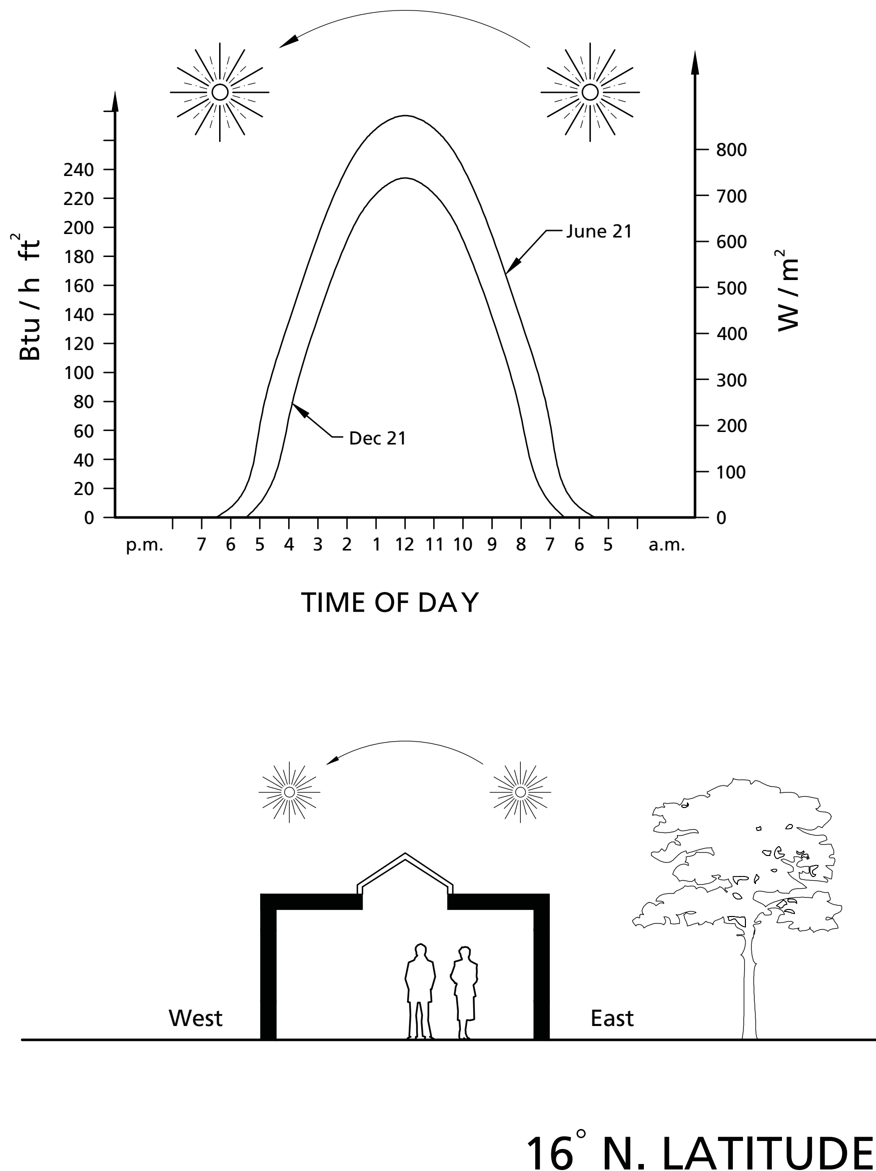


Figure 17.4g The graph shows the solar intensity on a skylight at 16°N latitude on both December 21 and June 21. Unlike the temperate zones, skylights n the tropics receive about the same amount of light every day of the year.

17.5 SHADING IN TROPICAL CLIMATES

Since there is no winter in the tropics and since it is too warm most if not all of the year, the whole year is usually the overheated period. Consequently, windows should be shaded all year long and not only from direct solar radiation but also from diffuse or reflected radiation. In humid climates, there is significant diffuse radiation from the sky, and in very dry climates there is usually significant radiation reflected from the bare ground or adjacent buildings. In all cases, the direct sun radiation should be blocked by external shading devices. In humid climates, the shading devices and especially the overhang should be extra long to block some of the hazy sky. However, in very dry regions, extending the overhangs does not block reflected radiation from the ground and adjacent buildings because the light is not coming from above. Instead, the most common traditional solutions are shutters and dense shade screens as mentioned in Section 17.2. Because both of these strategies severely block the view, they are much less acceptable today. As a result, in arid climates windows should be small, and a combination of overhang and low solar heat gain glazing could be used.

Since the shading strategies for north and south windows reverse at the equator, there is the potential for much confusion. For that reason, the following discussion of shading north and south windows will be in the format of a table with two columns: the left column for the Northern Hemisphere and the right column is for the Southern Hemisphere. *To avoid confusion, read only the relevant column.*

Unlike north and south windows, east and west windows cannot be fully shaded while maintaining a view. The only exception is a site where the windows are well shaded by neighboring high buildings or trees. For fixed east and west shading devices, the better the shade, the worse the view. For example, even an eggcrate shading device, which severely restricts the view, still allows some sun to enter at certain times of day and year. To maximize the view, which is almost mandatory in the modern world, movable shading devices should be used. For example, a very large overhang on a west window will provide both full shade and full view until the midafternoon, when the descending sun will start to outflank the overhang. At that point, an additional movable shading system must take over to block the low sun. See Figure 17.2b and Section 9.11 for various techniques to shade the low sun. Figure 17.5 shows a very effective strategy when balconies are

Table 17.5 North and South Window Shading in the Tropics

For Northern Hemisphere	For Southern Hemisphere
South Windows: South windows get easier to shade as one moves toward the equator from the Tropic of Cancer because the sun is progressively higher in the sky. Thus, south windows in the tropics need larger shading devices at the Tropic of Cancer than at the equator. The best shading device for south windows continues to be the overhang, and it is sized in the same manner as are south windows in Section 9.9 which is based on the Northern Hemisphere temperate zone. In most cases, the overhang can be fixed rather than movable.	North Windows: North windows get easier to shade as one moves toward the equator from the Tropic of Capricorn because the sun is progressively higher in the sky. Thus, north windows in the tropics need larger shading devices at the Tropic of Capricorn than at the equator. The best shading device for north windows continues to be the overhang, and it is sized in the same manner as are south windows in Section 9.9, even though it is based on the Northern Hemisphere temperate zone. In most cases, the overhang can be fixed rather than movable.
North Windows: North windows experience the opposite of south windows. North windows are easier to shade at the Tropic of Cancer than at the equator, where north and south windows experience the same solar exposure. At the Tropic of Cancer, small fins and a small overhang are sufficient. At the equator, the overhang is much larger while the fins are just a little bit smaller for full shading. Size the fins for north windows in the same manner as described in Section 9.13.	South Windows: South windows experience the opposite of north windows. South windows are easier to shade at the Tropic of Capricorn than at the equator, where south and north windows experience the same solar exposure. At the Tropic of Capricorn, small fins and a small overhang are sufficient. At the equator, the overhang is much larger while the fins are just a little bit smaller for full shading. Size the fins for south windows in the manner described for north windows in Section 9.13, even though it is based on the Northern Hemisphere temperate zone.



Figure 17.5 The smart condo owners in this Chongqing, China, apartment building added reflective curtains at the outer edge of their balconies to shade not only the windows but also the balcony.

present. An improvement on that strategy would be to extend the balconies to protect all the windows. Overhangs are especially appropriate in humid climates because they shade both direct and diffuse solar radiation, protect from heavy rain, and funnel more air into the building.

The design of east and west overhangs in the tropics is the same as in the temperate zones. However, fixed slanted fins are inappropriate in the tropics. Slanting the fins toward the southeast or southwest works well in the northern temperate zone because the summer sun rises in the northeast and sets in the northwest. At the equator, however, the sun must be shaded not only when it rises in the northeast but also when it rises in the southeast. And, of course, the same problem exists with the setting sun. Consequently, fixed fins are even less useful in the tropics than in the temperate zones. Although movable fins are better than fixed fins, they block the view much more than an overhang with backup movable shading for the low sun.

Since there is no ideal shading system for east and west windows, buildings should be designed with their long axis running east–west because that minimizes the size of the east and west facades. If windows cannot be avoided on those facades, the windows should be as few and small as possible. Also use windows in the "landscape" rather than "portrait" format, since short windows are easier to shade than tall windows.

East and west glazing should be minimized!

If shading is defined as blocking the sun, then the color of roofs and walls should be discussed along with shading. The best color by far is white because it has both a very high solar reflectance and a high infrared emissivity, which produces a very high solar reflective index (SRI) (see Section 9.21). The worst color is black, which transmits twice as much solar heat into the building as does white. Fortunately, most flat roofs now use white membranes.

For sloped roofs, smooth white metal provides the best protection against solar heating. Because clay tiles are popular in hot and wet regions, it is important to realize that white tiles are available and should be used. There is even a composite white tile that has an excellent SRI of 90. Common functional objections to sloped white roofs are that they get dirty and that they cause glare. Dirt accumulation on sloped roofs can be minimized by using a very smooth roofing material such as metal. Another option is to use a self-cleaning coating of titanium oxide, which acts as a cleaning catalyst when exposed to ultraviolet radiation. Although sloped roofs can on occasion cause glare, the problem is rarely severe; otherwise, all the roofs would not be white in Bermuda and Santorini. Furthermore, the author did not experience a glare problem when looking at buildings with white roofs in the United States. Dirt accumulation is not just an aesthetic problem, because roofs lose much of their reflectiveness when the get dirty. Fortunately, flat roofs are easy to clean.

White is the greenest color!

The color of walls is less critical because of the following reasons: black walls transmit only one and a half times as much heat as white walls; they are less exposed to the sun than the roof; they can be shaded by roof overhangs; and they are often shaded by adjacent trees and buildings. Nevertheless, white is still the best color for walls as well as roofs. White walls, which could be a greater glare problem than roofs, are quite popular all over the world, with one city proudly promoting them with its name—Casablanca (house-white). The author did not experience glare when he visited Casablanca. As a matter of fact, the worst glare is usually the result of large expanses of glass causing specular reflections of the sun. If the walls are well shaded, it is less important for them to be white. Instead, pale colors could be used.

Roofs should be white and walls as light-colored as possible!

17.6 DAYLIGHTING IN THE TROPICS

Daylighting can be more successful in the tropics than in the temperate zones because there is no winter when daylight hours are too few. Also, the north facade in the tropics receives much more daylight than it does in the temperate zones, and at the equator the north facade can harvest as much daylight as the south facade. The daylighting strategies in the tropics are just the same as in the temperate zone, except for the north facade, where windows should also have a light shelf of minimal size at the Tropic of Cancer, of the same size as the south windows at the equator, and of increasingly large size as one continues moving south toward the Tropic of Capricorn (the reverse is true in the Southern Hemisphere, of course).

As in the temperate zones, east and west windows are best minimized for both daylighting and shading benefits. Since heating is not required, all glazing should be of the “high light to solar gain” type. Near the Tropic of Cancer, clerestories should face north because they are easier to shade than clerestories facing any other direction, but at the equator north and south clerestories need equal shading. Since clerestories are vertical windows on or above the roof, they need to follow the same rules as windows.

Skylights, however, are quite different from windows and make more sense in the tropics than in the temperate zones. In the tropics, they supply a more even amount of daylight throughout the year, while in temperate climates they supply the most light in the summer and the least in the winter, which is exactly the opposite of what is desired. Skylights should be just large enough that electric lights can be turned off.

Because light shelves and skylights collect sunlight instead of skylight, windows can be quite small, thereby reducing the heat gain. However, sunlighting designs are more challenging than skylighting designs. For example, great care must be taken to spread the intense sunlight over a large area without creating glare (Colorplate 32). See Chapter 13 for a full discussion of daylight and sunlight.

17.7 PASSIVE COOLING

A passive cooling design will only save energy when it is too hot for comfort and air-conditioning is avoided or its use is minimized. Thus, if air-conditioning will be used all or most of the year, a passive cooling design is not appropriate and is even harmful, because a predominantly air-conditioned building must be designed differently from a passively cooled building. For example, in a hot and humid climate, an air-conditioned building must be very airtight, whereas a fully passively cooled building should leak like a sieve. The design of air-conditioned buildings in the tropics will be discussed in the next section.

As mentioned before, the first step in achieving thermal comfort in hot climates is, always has been, and always will be heat avoidance. In the case of a modern passively cooled building, heat avoidance is achieved by extensive use of shading, white roofs, light-colored walls, daylighting, efficient electric lighting, efficient appliances, a well-insulated roof, and the isolation of heat-producing elements (e.g., kitchens). An air-conditioned building would use all of these strategies, plus an efficient thermal envelope and a tight air-barrier. Since passive cooling design is very different for hot and dry climates and hot and humid climates, the design strategies for each will be discussed separately.

Heat avoidance is always the most important cooling strategy!

Passive Cooling in Very Hot and Dry Climates

Because of the large diurnal temperature range in very hot and dry climates (above 30°F or 17°C), the cool night air can be used not only for nighttime comfort but also to lower indoor temperatures during the day. The appropriate passive strategy is called night-flush cooling, because it utilizes large amounts of thermal mass exposed to the indoors from which heat is extracted by the cool night air that is brought into the building. The next day, the cooled thermal mass soaks up indoor heat to keep the indoor temperature from rising too high. To keep the sun and outdoor air from heating this mass, the windows are closed and shaded. Furthermore, the thermal mass should be protected from the outdoor air and sun by means of thermal insulation on its outdoor side. Performance can be further improved by using fans to bring in more outdoor air at night, and blowing it over the exposed thermal mass. Indoor fans (e.g., ceiling fans) are used during the day to extend the comfort zone to higher temperatures. For more information on night-flush cooling, see Section 10.9.

Passive Cooling in Very Hot and Humid Climates

Because of the small diurnal temperature range in very hot and humid climates (below 20°F or 11°C), the nighttime temperatures are not cool enough to significantly cool any thermal mass. Instead, outdoor air is brought into the building both during the night and during the day. The ventilation is not intended to cool the building but rather to cool people by increasing evaporative cooling on their skin. Consequently, this passive cooling strategy is known as comfort ventilation. For fully passively cooled buildings in hot and humid climates, thermal mass is a liability and should not be used. Natural ventilation is maximized by large windows and ventilating devices such as monitors on the roof. Windows must be placed at a location and height on a wall so that natural ventilation will pass over people and not the building structure. In sleeping areas or other locations where people are close to the floor, the windows must be equally low on the wall. Fans can be used to both increase the ventilation rate through the building and to blow more air over the occupants. For more information on comfort ventilation, see Section 10.8. See also Figure 10.9a, which shows the relationship between the diurnal temperature range and the choice of passive cooling systems.

There are plenty of regions where the climate is somewhere between very hot and dry and very hot and humid. Furthermore, in many places the climate is not constant throughout the year. There are also regions in the tropics that are still very hot but with medium humidity levels, and there are regions where part of the year it is very humid and another part very dry.

In climates with moderate humidity all year where the diurnal temperature range is medium (20°–30°F or 11°–17°C), thermal mass is still useful but less effective than in very dry climates. In such medium humidity climates, the windows should be wide open at night to provide both night-flush cooling and comfort ventilation, and closed during the day. Since the mass will not be cooled sufficiently, indoor temperatures will likely rise to uncomfortable levels in the afternoon. Indoor fans will then be a necessity. A modest amount of air-conditioning will also be desirable. Thus, for complete comfort in such a climate, a hybrid passive/active system will be best.

In regions where the climate varies from humid to dry during the year, the diurnal temperature range will also vary. Since it is not possible to have thermal mass at one time of year and not have it at another time, the decision to have mass depends on the length of the dry period. If it is dry for more than half the year, thermal mass could be used. The rules for when to open windows will change as the climate changes during the year. Windows will be open at night during the whole year but closed during the day when night-flush cooling is used during the dry part of the year.

Since in hot and humid climates passive cooling depends on natural ventilation, catching the maximum of wind is imperative. To maximize the wind, living areas should be as far off the ground as possible. If a building is not multistory, it can be raised on posts. Low vegetation should also be minimized, keeping only high canopy trees for shade. Since daytime ventilation is important in hot and humid climates, solar chimneys can be used to augment the wind (Section 10.16). To avoid adding to the humidity, avoid water elements in the landscape and provide good runoff for rainwater.

Except in special cases where the winds have a predominant direction, are fairly strong, and are fairly constant, a building should be oriented in an east–west direction to best respond to solar geometry. Thus, in most circumstances the long axis should run east–west.

For emphasis, it must be repeated that passive cooling will not work or will work only poorly if heat avoidance strategies like shading are not fully used. Heat avoidance is a necessary strategy in almost every sustainable design.

17.8 AIR-CONDITIONED BUILDINGS IN THE TROPICS

In very hot and dry climates, passive techniques are able to achieve a high level of thermal comfort without air-conditioning, but in humid climates the passive techniques are limited in the comfort they can achieve. It is important to realize that not all desert regions have a dry climate. Some coastal areas (e.g., along the Persian Gulf) receive almost no rain yet get humid air from offshore winds. Unfortunately for passive design,

most people live in humid climates because it rains there sufficiently to produce food or they live along humid coasts because of fishing and trade. Consequently, air-conditioning is popular in much of the tropics, and its use will increase as more people can afford it (Fig. 17.8a; see also Fig. 1.10c).

In very humid regions, the goal for either a modern or a developing society should be to minimize both the size of the air-conditioning equipment and the length of time that the equipment is using energy. In any hot climate, heat avoidance strategies should be fully used, and the passive cooling strategies should be used as much as possible. In addition, fully or partly air-conditioned buildings should be well insulated and airtight to keep hot and/or humid air from entering. Thermal mass is helpful with air-conditioning because it allows smaller equipment to maintain comfort. For example, the system can run at night to precool the mass for the next day. Thermal mass can also reduce expensive peak demand charges, because the air-conditioning equipment can be turned off for a while during the peak demand time because of the buffering effect of the mass.

The cooling load of a building is a function of its climate, its type, and its design. In dry climates, the very high temperatures require a very well insulated thermal envelope to keep the sensible heat out. In humid climates, where the maximum temperatures are lower, less insulation can be used, but there must be a greater emphasis on keeping the humid air out because of its high latent heat content (i.e., moisture). In either case, the insulation should be on the outdoor side of the thermal mass so that the mass absorbs indoor heat. Also, in all climates, indoor fans (especially ceiling fans) should be used to reduce the size and energy consumption of the air-conditioning system. Since indoor fans do not cool the building but only the occupants, the moving air should be aimed at the people. Fans should be controlled by occupancy sensors along with the lights.

Taylor's University Lakeside Campus in Malaysia is a case study of the challenges of building an air-conditioned complex in a hot and humid climate. The campus was built in 2010 and illustrates both good and bad design decisions in regard to the cooling load.

The design includes many good features. All of the buildings are white, and the administrative and classroom buildings have their long axes in the ideal east–west direction (Fig. 17.8b). The small but still problematic east and west facades are partly shaded by outdoor screens and large trellises made of vertical cables supporting vines (Fig. 17.8c). Large overhangs, canopies, and covered walkways allow students and faculty to move between buildings in shade (Fig. 17.8d). The student housing consists of two parallel seven-story buildings with the space between covered to protect from both rain and sun (Fig. 17.8e). The ends of this "courtyard" are open to maximize natural ventilation. The prominent and attractive stairs make walking between floors very convenient and pleasant.

The main weaknesses of the campus design include the wrong orientation for the student housing and inadequate outdoor shading of most windows (Fig. 17.8f). About half of



Figure 17.8a In hot and humid climates all over the world, people buy air conditioners as soon as they can afford them. Multiply this image by many millions (soon billions) to understand the scale of this expansion in the use of air conditioners. Unfortunately, too many people assume that shading is no longer necessary, as can be seen in the deterioration of many awnings or the lack of awnings once there is air-conditioning. Consequently, more planet-harming electricity is consumed than would be necessary if windows were properly shaded.



Figure 17.8b The classroom buildings at Taylor's University in Malaysia are properly designed by having their long axis running east–west and practically no windows on the short east and west facades. The outdoor projecting stairway is protected by a shade screen.



Figure 17.8c The east and west facades of the administrative building are protected by very large overhangs and vine trellises. This photo was taken shortly after the completion of construction. The vines should be doing great shading by now.



Figure 17.8d The student housing, unfortunately, was not oriented correctly and the east and west windows are not even shaded. But another good feature is that all of the buildings on this campus are connected by shaded passages.



Figure 17.8e A shaded and protected atrium type of space is created between the two blocks of student housing. The windows facing this interior space are well shaded.



Figure 17.8f A major weakness in the design is the inadequate shading of many windows. Although the air-conditioned penthouses are enclosed by very low solar gain glazing, they are unbearably hot inside because of both solar and conduction gains. Instead, the penthouses should have had much less glass and extensive outdoor shading.

all student housing windows are fully exposed to the east and west sun (Fig. 17.8d). Although the academic and administrative buildings are oriented correctly, their windows are without outdoor shading devices. While low solar gain glazing was used, the excessive use of glazing and lack of outdoor shading devices still create a huge unnecessary cooling load.

Because of tradition, many stores and restaurants in Malaysia do not use storefronts to keep out the hot and humid air. Many restaurants on campus, for example, have their seating both indoors and outdoors with no barrier between them. Thus, the hot and humid outdoor air moves freely indoors, and the air-conditioned air freely spills to the outdoors. Before air-conditioning this arrangement was logical, but now it is a serious waste of energy and is not sustainable.

A questionable design feature of the campus is that all corridors are shaded but open to the outdoors. Thus, all classrooms open to the un-air-conditioned corridors. The benefit is that the building volume to be cooled has been reduced, but the problem of infiltration of hot and humid air has been greatly increased. The author believes that air-conditioned corridors would have been more energy efficient because both the infiltration and exposed surface area of the buildings would have been reduced. The author found using the elevators especially uncomfortable because

the elevator shafts and landings were exposed to outdoor air, and consequently the elevator doors always opened to outdoor air. The elevator cab fan and possible air-conditioning could not keep up with the heat gain.

Overall, the Lakeside campus is a success. However, the campus could have been much more energy efficient if there had been more emphasis on orientation, shading, and the problem of the excessive infiltration of hot and humid air.

17.9 CONCLUSION

The design of a tropical building is very similar to the design of a building in the hot parts of the temperate zones where winter heating is not required. The main differences from such a temperate design are based on sun angles, with the differences being most extreme at the equator and least extreme at the Tropic of Cancer and the Tropic of Capricorn.

Table 17.9 presents a summary of the design strategies appropriate for the hot and dry and hot and humid tropics in the quest of minimizing the energy consumption of buildings and in maximizing their sustainability.

Table 17.9 Summary of Design Strategies for the Tropics

Topic	Hot and Dry	Hot and Humid
Climate		
annual temperature range	45°–130°F (8°–55°C)	65°–100°F (18°–37°C)
diurnal temperature range	>30°F (>17°C)	<20°F (11°C)
rainfall	little	much (except some coastal areas)
wind	varies greatly with microclimate	varies greatly with microclimate
clouds	few	many
sky	clear	hazy
source of most sunlight	direct and reflected	direct and diffuse
Form and Plan		
best plan	elongated rectangle with width mainly determined by access to daylight	slender elongated rectangle to allow cross ventilation and daylighting less slender rectangle if air-conditioned
courtyard	very desirable	not desirable because it blocks cross ventilation
spacing between buildings	minimize so that buildings can shade each other and streets	maximize to allow for natural ventilation
Ventilation		
at night	yes	yes
during the day	no	yes
purpose	to cool building and people at night	both day and night but only to cool people
shutters	for use during the day to block both sun and air	use louvered shutters during the day to block sun but not air
Windows		
purpose	for view, daylighting, and natural ventilation mainly to cool thermal mass at night	for view, daylighting, and natural ventilation to pass over people both day and night
number	few	many
size	small	large
height on wall		
a. for daylighting	high	high
b. for natural ventilation	high, to cool ceiling mass	at height of people in spaces
Shading of Windows		
purpose	shade both direct and reflected radiation	shade both direct and diffuse sky radiation
which orientation?	all	all
outdoor shading	all	all
indoor shading	as backup and glare control	as backup and glare control
movable shading	on east and west windows for low sun	on east and west windows for low sun
plants	if sufficient water is available	as much as possible
Shading of Roof		
desirable	yes	yes
how	roof canopy or PV panels	roof canopy, vegetated roof, or PV panels
by color	very highly reflective white roof should be used	white roof is highly desirable

(*Continued*)

Topic	Hot and Dry	Hot and Humid
Shading of Walls		
desirable?	very much	yes
how	mostly by having buildings shade each other by being very close to each other	mostly by large roof overhangs, porches, high trees, or trellises
color	white is highly recommended	white, especially if other shading is inadequate
Daylighting		
source of light	mostly from direct and reflected	mostly from direct and bright hazy sky
intensity of source	a little from the blue sky	a little from reflected
	very intense direct	intense direct
	intense from reflected	intense diffuse
	not intense from sky	not intense from reflected*
Thermal Mass		
appropriate?	yes	no for full passive cooling
purpose	to be cooled at night	yes for air-conditioned building
	to soak up indoor heat during the day	act as buffer to reduce peak air-conditioning load
		allow nighttime precooling
area	maximize exposed area	maximize exposed area in air-conditioned building
thickness	at least one 1 ft (0.3 m)	at least 6 in. (15 cm)

*except in cases where there is water, or man-made objects such as reflective buildings or light-colored streets.

KEY IDEAS OF CHAPTER 17

1. The tropics lie between the Tropic of Cancer (23.5°N latitude) and the Tropic of Capricorn (23.5°S latitude).
2. Traditional architecture in hot and dry climates consists of massive wall and roof structures, small windows, narrow alleys, and shading devices.
3. Courtyard houses are appropriate for hot and dry climates.
4. Traditional architecture in hot and humid climates consists of lightweight structures, maximum natural ventilation, and shading devices.
5. Courtyard buildings are not appropriate for hot and humid climates.
6. Tropical climates vary from temperate climates in that there are no winters. Summers in tropical climates are much as are summers in temperate climates. Summers are year-round at the equator and get slightly shorter toward the Tropics of Cancer and Capricorn.
7. Avoid east and west windows because they cannot be shaded well.
8. The shading requirement is identical for north and south orientations at the equator but varies somewhat toward the Tropics of Cancer and Capricorn.
9. The shading requirements for north and south facades reverse south of the equator.
10. Instead of skylights use shaded north and south clerestories.
11. The greenest color is white, especially for the roof.
12. Daylighting strategies for east and west windows are similar to those for the temperate climates. However, the daylighting design for north and south windows is different at the equator, where strategies should be the same for both.
13. Heat avoidance is the number-one cooling strategy.
14. Passive cooling strategies are the same as those in temperate climates (see Chapter 10).
15. When air-conditioning cannot be avoided, it should be minimized in both size and necessary duration of use, mostly by heat avoidance strategies.
16. The tradition of open storefronts in many parts of the tropics is not sustainable when air-conditioning is used.
17. Heat avoidance and shading are the two most important strategies for creating low energy sustainable buildings in hot climates!

Resources

FURTHER READING

Lauber, W. *Tropical Architecture: Sustainable and Humane Building in Africa, Latin America, and South-East Asia*. Prestel Verlag, 2005.

Salmon, C. *Architectural Design for Tropical Regions*. John Wiley & Sons,. 1999.

Tan, H. B. *Tropical Architecture and Interiors: Tradition-Based Design of Indonesia, Malaysia, Singapore, Thailand*. Page One Publishing, PTE Ltd., 1994.

CHAPTER 18

RECOMMENDED LOW ENERGY CASE STUDIES

Homo sapiens is perceived to stand at the top of the pyramid of life, but the pinnacle is a precarious station.
Patrick Leahy, U.S. senator

18.1 INTRODUCTION

My favorite definition of education is "learning what you didn't know you didn't know." After all, if you know that you don't know something, you can look it up, and that has become especially easy because of the World Wide Web. However, if you don't know that you don't know, then you will be content in not knowing. Consequently, the objective of this chapter is to make the reader aware of some buildings that are worth knowing about. The reader can then seek more information on the Web, in books, or in journals.

The following case studies are a limited personal selection of buildings that have focused on achieving heating, cooling, and lighting in a sustainable, low energy way. It should not be assumed that the buildings in the following list are the only good examples available. The list contains a small collection of buildings that the author happens to be aware of.

18.2 CASE STUDIES

A. Office Buildings

1. **Name of building**: Heifer International Center
   Type of building: headquarters, offices
   Location: Little Rock, Arkansas
   Year: 2006
   Architect: Polk, Stanley, Rowland, Curzon, Porter Architects
   Key energy features: orientation, daylighting, light shelves, shading, under-floor air distribution, attractive stairs to minimize use of elevators

2. **Name of building**: 1 Bligh Street
   Type of building: office skyscraper
   Location: Sydney, Australia
   Year: 2011
   Architect: Architectus and Ingenhoven Architects
   Key energy features: naturally ventilated atrium, double-skin facade, dynamic shading, daylighting, chilled beams, trigeneration, PV

3. **Name of building**: Council House 2
   Type of building: office
   Location: Melbourne, Australia
   Year: 2006
   Architect: joint venture with Melbourne City Council and Design Inc.
   Key energy features: operable shutters for shading, operable windows, under-floor ventilation, radiant cooling, chilled beams, night-flush cooling, evaporative cooling, cogeneration, phase change heat storage
   Important weaknesses: passive rooftop exhaust turbines that did not work

4. **Name of building**: Research Support Facility
   Type of building: office
   Location: Golden, Colorado
   Year: 2012
   Architect: RNL Design
   Key energy features: orientation, daylighting, task/ambient lighting, transpired solar collectors, remote mass thermal storage, cross ventilation, night-flush cooling, evaporative cooling, radiant heating and cooling, under-floor ventilation, precast insulated panels, large PV system

5. **Name of building**: Bullitt Center
   Type of building: office
   Location: Seattle, Washington
   Year: 2011
   Architect: Miller Hull Partnership
   Web address: http://bullittcenter.org
   Key energy features: PV, daylighting, natural ventilation with operable windows, ground source heat pump, radiant heating and cooling, heat recovery

6. **Name of building**: The Emerald People's Utility District Headquarters
   Type of building: office
   Location: Eugene, Oregon
   Year: 1987
   Architect: Equinox Design and WEGROUP, PC, Architects
   Key energy features: passive heating and cooling, daylighting, thermal mass, vegetative shading

7. **Name of building:** Gregory Bateson Building
   Type of building: office
   Location: Sacramento, California
   Year: 1981
   Architect: Office of the State Architect for California
   Key energy features: passive heating and cooling, daylighting, dynamic shading, atrium, thermal mass, antistratification devices

8. **Name of building:** Commerzbank
   Type of building: 62-story office
   Location: Frankfurt, Germany
   Year: 1997
   Architect: Foster and Partners
   Key energy features: natural ventilation, daylighting, sky gardens atrium, double skin (climate facade), dynamic shading
   Important weaknesses: triangular floor plan does not utilize orientation

9. **Name of building:** Save the Bay Center
   Type of building: offices, headquarters
   Location: Providence, Rhode Island
   Year: 2005
   Architect: Croxton Collaborative Architects
   Key energy features: daylighting, clerestories, shading, vegetated roof
   Important weaknesses: part of building is not oriented enough to south

10. **Name of building:** Lewis & Clark State Office Building
    Type of building: office
    Location: Jefferson City, Missouri
    Year: 2005
    Architect: BNIM Architects
    Key energy features: orientation, daylighting, light shelves, operable windows, prominent attractive stairs, integrative design, few east and west windows

11. **Name of building:** Alberici Corporate Headquarters
    Type of building: office
    Location: Overland, Missouri
    Year: 2004
    Architect: Mackey Mitchell Architects
    Key energy features: existing warehouse converted into office space, solar hot water, daylighting, natural ventilation, heat recovery ventilation, added sawtooth wall to correct for poor orientation

12. **Name of building:** Manitoba Hydro Place
    Type of building: office (18 floors)
    Location: Winnipeg, Canada
    Year: 2009
    Architect: Kuwabara Payne McKenna Blumberg Architects
    Key energy features: passive solar heating, double-skin facade, operable windows, solar chimney, geothermal, 6-story-high winter gardens, radiant ceiling, water feature for both humidifying and dehumidifying, dynamic shading, under-floor displacement ventilation

13. **Name of building:** Unilever Headquarters
    Type of building: office (7-story)
    Location: Hamburg, Germany
    Year: 2009
    Architect: Behnisch Architekten
    Key energy features: double-skin facade with plastic outer skin plastic, radiant cooling system, under-floor ventilation, atrium

B. Libraries

1. **Name of building**: National Library
   Type of building: library
   Location: Singapore
   Year: 2006
   Architect: T. R. Hamzah & Yeang
   Key energy features: daylighting, light shelves, shading, white walls, shaded pedestrian areas, some parts only naturally ventilated, only some parts air-conditioned, ceiling fans, atrium naturally ventilated, vegetated balconies

2. **Name of building:** Phoenix Central Library
   Type of building: library
   Location: Phoenix, Arizona
   Year: 1995
   Architect: William P. Bruder and DWL Architects and Planners
   Key energy features: form and orientation, dynamic shading, daylighting

3. **Name of building:** Cambridge Public Library Addition
   Type of building: library
   Location: Cambridge, Massachusetts
   Year: 2009
   Architect: William Rawn Associates
   Key energy features: double skin (3 ft [0.9 m] wide) can be vented for summer or sealed for winter, dynamic shading

C. Institutional Buildings

1. **Name of building**: The Centre for Interactive Research on Sustainability at the University of British Columbia
   Type of building: office
   Location: Vancouver, Canada
   Year: 2011
   Architect: Perkins + Will
   Key energy features: daylighting, cross ventilation, vegetated roof, operable windows, heat recovery from exhaust of neighboring laboratory building, geo-exchange, green (plants) exterior screen on west windows, building-integrated PV on sunshades, solar hot water

2. **Name of building**: Chandler City Hall
   Type of building: municipal center
   Location: Chandler, Arizona
   Year: 2010
   Architect: SmithGroup
   Key energy features: artistic shading, daylighting, under-floor air distribution, employee education for using the operable building, cooling tower as waterfall feature

3. **Name of building**: Global Ecology Center
   Type of building: labs and offices
   Location: Stanford, California
   Year: 2004
   Architect: EHDD Architecture
   Key energy features: orientation, water cooled by spraying on roof at night, radiant heating and cooling, daylighting, natural ventilation, light shelves, heat recovery, shading, high-performance glazing, cooling tower

4. **Name of building:** Sino-Italian Ecological and Energy Efficient Building (SIEEB)
   Type of building: research (offices and laboratories)
   Location: Beijing, China
   Year: 2007
   Architect: Mario Cucinella Architects
   For more imformation: See *Towards Zero Energy Architecture*, by Mary Guzowski
   Key energy features: solar orientation, dynamic shading, passive solar, daylighting, thermal mass, operable windows, PV, double skin

5. **Name of building**: Aldo Leopold Legacy Center
   Type of building: office, with meeting rooms, library, and lecture rooms
   Location: Baraboo, Wisconsin
   Year: 2007
   Architect: Kubala Washatko Architects
   Key energy features: shading, cross ventilation, daylighting, ground source heat pump, radiant slab, earth tubes, solar hot water, passive solar

6. **Name of building:** Blue Ridge Parkway Destination Center
   Type of building: visitor center
   Location: Asheville, North Carolina
   Year: 2008
   Architect: National Park Service and Lord, Aeck & Sargent, Inc.
   Key energy features: passive solar, Trombe walls, energy recovery, radiant heating, vegetated roof,

daylighting, operable windows, orientation

7. **Name of building:** Desert Living Center & Gardens at the Springs Preserve
   Type of building: education and research facility
   Location: Las Vegas, Nevada
   Year: 2008
   Architect: Lucchesi Galati
   Key energy features: orientation, passive solar, daylighting, massive walls, shading, PV-shaded parking, night-flush cooling, no mechanical systems

D. Religious Buildings

1. **Name of building**: Congregation Beth David Synagogue
   Type of building: synagogue
   Location: San Louis Obispo, California
   Year: 2006
   Architect: San Luis Sustainability Group
   Key energy features: passive solar, Trombe wall, passive cooling, natural ventilation, daylighting, thermal mass, automated windows

E. Museums

1. **Name of building**: California Academy of Sciences
   Type of building: museum
   Location: San Francisco, California
   Year: 2008
   Architect: Renzo Piano Building Workshop and Stantec Archtecture
   Key energy features: vegetated roof, daylighting, building-integrated PV, dynamic shading, displacement ventilation, natural ventilation, openable skylights
   Important weaknesses: skylights instead of clerestories

F. Commercial

1. **Name of building:** The Real Goods Solar Living Center
   Type of building: retail store
   Location: Hopland, California
   Year: 1996
   Architect: Van der Ryn Architects and Arkin Tilt Architects
   Key energy features: passive heating and cooling, daylighting, straw bale, regenerative landscaping, vegetative shading

G. Schools

1. **Name of building:** Colorado Mountain College
   Type of building: school
   Location: Glenwood Springs, Colorado
   Year: 1981
   Architect: Peter Dobrovolny, AIA, of Sunup Ltd.
   Key energy features: passive heating and cooling, daylighting, earth sheltering, dynamic shading
   Important weaknesses: not enough shading of Trombe walls

2. **Name of building**: Portland Community College Newberg Center
   Type of building: classrooms
   Location: Newberg, Oregon
   Year: 2011
   Architect: Hennebery Eddy Architects
   Key energy features: orientation, passive solar, radiant heating, ventilation stacks for natural ventilation, daylighting, shading, thermal mass, large ceiling fans

3. **Name of building:** Camp Arroyo
   Type of building: multibuilding camp to teach green design
   Location: Livermore, California
   Year: 2001
   Architect: Siegel & Strain
   Key energy features: cross ventilation, daylighting, passive solar

4. **Name of building:** Lillis Business Complex, University of Oregon, Eugene
   Type of building: classrooms and connector
   Location: Eugene, Oregon
   Year: 2003
   Architect: SRG Partnership
   Key energy features: daylighting, daylit classrooms, dynamic shading, night-flush cooling, natural ventilation, thermal mass, building-integrated PV in curtainwall, clerestories
   Important weaknesses: excessive stratification in atrium

5. **Name of building:** Creative Arts Building
   Type of building: school for creating all kinds of art
   Location: Western North Carolina
   Year: 2013
   Architect: Innovative Design
   Key energy features: orientation, daylighting, natural ventilation, high mass, well insulated, active solar collectors, domestic hot water, heating, and absorption cooling

H. Entertainment

1. **Name of building:** Winspear Opera House
   Type of building: auditorium
   Location: Dallas, Texas
   Year: 2009
   Architect: Foster & Partners
   Key energy features: huge shading 63 ft (19 m) high canopy around the building shading both glass walls and public space, displacement ventilation

CHAPTER 19

CHECKLIST FOR DESIGNING INTEGRATED SUSTAINABLE BUILDINGS

We are evaporating our coal mines into the air.
Svante Arrhenius, Swedish chemist, 1896

19.1 INTRODUCTION

A building design is the result of innumerable decisions, and the success of the final design depends on which alternatives are chosen at every step of the design process. However, because the most important decisions are made at the front end of the schematic design stage, this book is written to provide that information and those concepts needed at that early stage with an emphasis on designing low energy sustainable buildings. Even if all of the relevant knowledge has been acquired, it is still a major challenge to know what applies to a specific project and at what point in the design process a particular decision should be made.

The checklist below is a guide for the designer about what important options are available for the heating, cooling, and lighting of buildings. To achieve a sustainable integrated design, it is important that the best alternative is chosen at the correct point in the design process. The single best example of how a particular decision has a major impact on many future decisions and the success of the final design is the choice of orientation. Only the correct choice will allow for high-performance passive solar, shading, and daylighting, and for their successful integration.

The checklist is arranged as much as possible in the order that the decisions are made in the schematic design process of a building.

19.2 SITE SELECTION

1. Consider a site that allows the building to be oriented along an east–west axis.
2. Consider a site with winter solar access, if the building will need a heating system.
3. Consider a site that is shaded in the summer by neighboring buildings or trees to the east and west.
4. Determine if there are legal or physical restrictions to the site that could prevent the use of solar collectors, white roofs, etc.

19.3 FORM

1. Consider an elongated rectangle with its long axis running east–west.
2. Consider a compact design to minimize surface area and building materials. Aesthetics achieved through complex forms is less sustainable than aesthetics achieved through ornamentation.
3. Consider limiting the width (depth) of the building to allow full use of daylighting and/or cross ventilation.
4. Consider using an atrium to get light and views to the center of a large compact building.
5. Consider a covered atrium to reduce the exposed surface area of the building (i.e., achieve greater compactness).
6. Avoid using an articulated facade that would block access to the winter sun. For example, avoid wings toward the south which would shade the main building in the winter.
7. Consider building projections on the east and west to allow north and south windows instead of east and west on those facades.
8. Consider the fact that a solar-responsive building will have facades that vary with orientation. The east and west facades should have the fewest windows and north and south the most.
9. When daylighting is very important, consider a form that will maximize the area of the top floor (i.e., maximize the building footprint) because the best daylighting is through the roof.

19.4 PLAN

1. Consider placing rooms that benefit from winter sun on the south side of building (e.g., living rooms, classrooms, and offices).
2. Consider placing rooms that benefit from being cold on the north side of the building (e.g., kitchens, bedrooms, computer rooms, and offices that generate a lot of heat).
3. Consider using buffer spaces on the east and west sides of a building (e.g., garage, storage, and fire stairs).
4. Consider discouraging healthy people from using elevators and escalators when traveling only one or two floors in order to both save energy and increase healthy exercise. Use beautiful prominent stairs while making elevators and escalators less prominent and less attractive.
5. Use an open floor plan to maximize daylight and natural ventilation.

19.5 WINDOWS

1. Consider placing all or most windows on the north and south facades. Place most windows on south facade for buildings that will need much winter heating. Place most windows on north facade for buildings that need little or no winter heating.
2. If windows are needed on the east and west facades, consider using as few as possible and making them as small as possible.
3. Consider making east and west windows as short as possible because they are easier to shade with overhangs (i.e., landscape rather than portrait). Consider using ribbon windows.
4. Consider placing windows as high on wall as possible for greater daylight penetration.
5. Consider using operable windows in all buildings. However, there should be a system that shuts down the air-conditioning and heating equipment if any windows are open. For example, use security-type switches on windows that are in series with the thermostat in that zone.
6. Do not use windows with an R-value of less than 3 (double glazing with low-e) unless indoor night insulation is provided. Consider using windows with higher R-values in cold climates.

19.6 DAYLIGHTING

1. Remember that quality is more important than quantity.
2. Consider using light shelves on south windows, and on any east and west windows that were necessary.
3. Consider high ceilings that allow for high windows.
4. Consider using clerestories for top lighting. Use south-facing clerestories in buildings that need winter heat or use north-facing clerestories for buildings that do not need winter heat.
5. Avoid using skylights because they collect more sun in the summer than in the winter.
6. Consider using an atrium to bring light to the center of a building. A covered atrium should use north- or south-facing clerestories depending on whether heating is required or not.
7. Use baffles or louvers with south-facing clerestories to control glare and puddles of sunlight.
8. Consider using light tubes through the roof to illuminate small core areas.
9. Consider using high R-value light-transmitting translucent panels for the roof or a section of the roof.
10. On windows, consider using indoor blinds and shades mainly to control glare and light levels.
11. Consider using prismatic daylighting glass in upper windows instead of light shelves.
12. To avoid glare, avoid translucent walls or windows except near the ceiling of high spaces like a gymnasium.
13. Consider using as much borrowed light as possible by using glass partitions and glass doors, as was common in the first half of the twentieth century.
14. Consider using very light-colored (white) paved areas just outside first-floor windows to reflect more light further into the building.
15. Remember that daylighting will not reduce energy consumption unless the electric lights are turned off. Thus, automatic controls are a requirement.

19.7 SHADING

1. Consider using overhangs for south, east, and west windows. Use fixed overhangs for buildings that have no heating system, and movable overhangs (e.g., awnings) for buildings that do have a heating system.
2. Consider using outdoor venetian blinds or roller shades in addition to or instead of overhangs to block the low east and west sun.
3. Avoid vertical fins on the east and west windows, since they work less well than horizontal louvers. Use fins on north windows or to keep sun from outflanking overhangs.
4. Consider using trees and other plants to shade east and west windows. Do not use trees or other plants to shade the south windows if passive solar will be used. Also do not shade the roof since solar hot water and solar electric (PV) panels would be shaded.
5. Test your shading design to make sure the sun cannot outflank it. Consider using a heliodon.
6. Consider also shading the roof, walls, and land around the building.
7. Consider using plants for shading walls. In tall buildings, a vegetated wall (especially east and west) may be more important than a vegetated roof. Vines may be the best option for green walls.
8. Understand that outdoor shading is four times better than indoor shading.
9. Only use low solar-heat gain glazing if the building has no heating system. For buildings with heating systems, use high solar-gain glazing, especially for south windows, to make passive solar possible.
10. Windows should be fully shaded during the whole overheated period of the year.
11. The south windows of buildings with heating systems should be fully exposed to the sun during the whole underheated period of the year by means of movable shading devices. Consequently, do not use large roof overhangs or other fixed shading devices on south windows.

19.8 COLOR

1. Consider using white for sloped as well as flat roofs, since it reduces the heat gain by 50 percent compared to black roofs. If the roof is flat, use a white membrane, and if it is sloped, use white metal. White roofs are best even in cold climates because the winter and summer conditions are not symmetrical. The low winter sun sees much less of the roof than the high summer sun, and there are about sixteen solar heating hours per day in the summer and only about eight hours in the winter.
2. Consider using high-tech “cool roof” shingles or tiles if white metal roofing is not an option. Use the highest solar reflectivity index (SRI) possible.
3. Consider using white or very light-colored walls. Different orientations could have different colors, with north being the darkest and east and west the lightest.
4. Consider using light-colored paving instead of asphalt around the building to reflect more sunlight back into space and up into windows.
5. Consider minimizing paving and maximizing vegetated areas around building.
6. Ceilings should almost always be high reflectance white.
7. Consider using light-colored (white) walls, furniture, and floor finishes to help create the best and most efficient lighting. The light-colored surfaces also create the perception of a well-lit space using the least amount of light.

19.9 THERMAL ENVELOPE

1. Consider using more insulation than is now recommended or considered economical, because having more insulation will be economical in the future, and insulation is very hard to add at a later date.
2. Avoid as many heat bridges as possible and especially large ones.
3. Avoid structural penetration of the thermal envelope like beams or slabs that support balconies. Instead, hang balconies. The structure should be on the indoor side of the insulation.
4. All ducts and pipes should be on the indoor side of the thermal envelope.
5. Consider placing all insulation on the exterior side of steel studs or joists and not in the space between them. Steel studs derate cavity insulation by 50 percent.
6. Consider using SIP panels whenever possible.
7. Consider using very high R-value windows unless windows are used to collect passive solar because solar transmission declines with increasing R-value.
8. In cold climates, consider using double glazing without the low-e coating on south windows, because low-e coatings lower the solar heat gain coefficient. Instead supplement the windows with indoor night insulation.
9. Thermal mass should be on the indoor side of the insulation but not insulated from the indoor air.
10. Thermal mass is not a substitute for insulation in modern buildings.
11. Consider earth sheltering, especially if the site is on a south-facing slope where much sunshine can be harvested with only a few small windows. Earth sheltering also protects against storms and noise. Avoid earth berms with penetrations because each opening in the berm is a major heat bridge.

19.10 THERMAL MASS

1. Consider using indoor thermal mass to support passive solar, passive cooling, and air-conditioning.
2. The exposed indoor area of mass is much more important than the thickness of mass.
3. For passive solar, the best mass is usually the floor exposed to direct sunlight.
4. For passive cooling and air-conditioning, have mass exposed to airflow. Consider using exposed concrete joists or T beams to increase the exposed surface area.
5. Consider using phase change material (PCM) or water as compact substitutes for concrete. Water in translucent or transparent tubes can also provide aesthetic benefits.
6. Do not cover thermal mass with any insulating material such as carpets or acoustical materials. Instead of carpets, have occupants wear cushioned slippers, as is common in some Asian countries. Slippers are quiet, comfortable, and promote indoor air quality. Instead of acoustical insulation on the ceiling, hang the acoustic panels in vertical planes and use acoustical partitions.
7. Consider burying plastic tubes filled with water in concrete floor slabs to reduce the amount of concrete required as well as to increase the heat storage capability.

19.11 GLAZING

1. Consider "tuning the glazing" by using a different glazing type on each facade of a building and even in different parts of a window.
2. When daylighting but not heat is desired, use high light-to-solar-gain ratio glazing in the daylight windows (e.g., glazing above light shelf and in south-facing clerestories) and consider using low solar transmission (including light) for the view windows if winter passive solar is not desired.
3. When passive solar is desired, use very high solar-gain glazing for south windows and possibly east and west windows. Also use outdoor shading in the summer and indoor night insulation in the winter. Use high R-value windows on the north facade.
4. Consider using insulated translucent panels instead of glazing for clerestories and small skylights. Because they can cause glare, do not use translucent panels on walls unless they are used near the top of very high walls (e.g., in a gymnasium).
5. Do not use reflective glazing in any situation where the reflected light can cause a problem such as glare and overheating for neighbors or the area around a building. Never use reflective glazing on any concave facade because the sunlight will be concentrated.
6. Single glazing should not be used in any heated or cooled building. Remember that single glazing has an R-value of 1 while a good wall will have an R-value of about 15. Except for south windows used for passive solar, the lowest R-value should be R-3.
7. Remember that conventional glazing does not respond to changes in the environment. For example, conventional glazing cannot have high solar transmission in the winter and low transmission in the summer. Instead, use dynamic systems. The following are some examples:
   a. Movable shading devices such as awnings for full summer shade and full solar access in the winter.
   b. Operable louvers or venetian blinds to control solar access to respond to changing sun angles and cloud-cover changes.
   c. Night insulation that allows high solar gain during the winter day and provides low heat

loss at night. Night insulation can also reduce daytime heat gain in the summer if views and daylight are not a high priority as in a residence when nobody is at home.

8. Be aware that although tinted single glazing reduces the transmission of solar radiation, it is not very effective in reducing solar-caused heat gain, because tinted glazing absorbs the sun, gets hot, and transmits much of that heat indoors.
9. Be aware that the use of outdoor shading devices are best at blocking direct solar radiation, while low solar heat-gain glazing is best to block diffuse radiation from the lower sky and reflected radiation from the surroundings.
10. Consider the aesthetic benefits of external shading devices since they enrich the 3-D texture of the facade.
11. Consider the high cost and limitations of dynamic glazing at this time.

19.12 AIR BARRIER

1. Use an air barrier to minimize infiltration and water penetration.
2. Consider using windows and doors with excellent weatherstripping.
3. Consider using a vestibule or revolving door at the entrance.
4. Consider using a heat exchanger ventilation system instead of infiltration to maintain indoor air quality.

19.13 PASSIVE SYSTEMS

1. Consider transpired solar collectors for preheating ventilation air.
2. Consider using Trombe walls for solar heating without light.
3. Consider using a mixture of direct gain (i.e., south windows) and Trombe walls to maximize solar heating while controlling the amount of solar radiation (e.g., light) entering the building.
4. Consider using solar and stack-effect chimneys to augment the wind for natural ventilation.
5. Consider using cowl-type roof ventilators, which can rotate like a wind vane to maximize the natural ventilation.
6. Consider using exterior wing walls to divert the wind in order to increase natural ventilation.

19.14 ELECTRIC LIGHTING

1. Remember that quality is more important than quantity.
2. Keep all surface colors as light as possible. Ceilings should almost always be a high reflectance white.
3. Consider using task ambient lighting for the highest quality and the least energy consumption. LEDs make great task lights.
4. Consider the fact that LED lights are not always the best choice at this time. That may or may not change in the future. LEDs are best for spotlighting, while fluorescent lamps are often the best for area lighting.
5. Remember that lighting efficiency is not just a function of the lamp efficacy but also of the performance of the lighting fixture and room finishes.
6. Remember that veiling reflections are a major lighting problem. Do not place fixtures so that the angle of incidence equals the angle of reflection relative to the eye. Geometry is the key.
7. Because the brightness of the walls is the key factor in the perception of room brightness, very light colors should be used. Remember that a room with mostly dark surfaces cannot be made to look well-lit no matter how much light is supplied.
8. Consider avoiding light pollution outdoors, since it is both objectionable and inefficient. All outdoor light should end up where it is needed or useful (e.g., walkways, parking areas, building illumination) and not in the sky or on a neighbor's property. Building illumination should be from the top down rather than from the bottom up, because spilled light will then illuminate the ground rather than the sky. Use a building "crown" to hold light fixtures away from the building so that they can be aimed down toward the building.
9. Consider using occupancy sensors to turn off lights, personal fans, and personal heaters when not needed.
10. Consider automatically reducing the illumination level in corridors and stairwells at night or when no one is present.
11. Do not use indirect lighting fixtures unless the wall or ceiling is white or a very light color. For example, do not use sconces on colored walls.
12. Do not use indirect up lights unless they will be cleaned often. This is especially true outdoors.

19.15 MECHANICAL EQUIPMENT

1. All ductwork must be on the indoor side of the thermal envelope.
2. Consider a radiant floor heating system in cases where mechanical cooling is not required.
3. Consider using a geo-exchange system for both heating and cooling.
4. Consider natural ventilation to supplement mechanical cooling. Except in homes, an interlock system should prevent mechanical heating or cooling if the windows are open.
5. Consider using much larger ducts than normal because they will reduce the required fan power, which is quite substantial.
6. Minimize the number of bends in the ductwork. The initial design of the ductwork and structure should be integrated to allow ductwork to be as straight as possible.

7. Consider placing the MER in a central location to minimize the length of ducts.
8. Consider using highly insulated walls, roofs, and windows so that the mean radiant temperature will allow the use of lower temperatures in the winter and higher temperatures in the summer while maintaining complete comfort. Thus, insulation saves energy in two distinct ways: less direct heat loss/gain because of a higher R-value, and less heat loss/gain resulting from lower (higher) thermostat settings, which create a smaller temperature difference between indoors and outdoors.
9. Consider a heat exchanger to recover both sensible and latent heat otherwise lost by ventilation.
10. Consider using displacement ventilation for greater efficiency and better air quality.
11. Consider heat storage so that the compressors can run at night when they operate more efficiently and electric rates are lower. Heat storage can also help reduce peak demand charges. Consider using ice instead of water since it is a much more compact heat storage medium.
12. Consider allowing individual environmental control for each workstation since people's thermal comfort and lighting needs vary greatly. Supplying a fan at each workstation will allow the thermostat to be set higher in the summer. A heat lamp and/or foot heater at each workstation could allow lower thermostat temperatures in the winter, since these devices only heat the person and not the whole space. These devices should be controlled by an occupancy sensor.
13. Consider using building materials, furniture, and cleaning supplies with low VOCs so that ventilation can be minimized, since it is a major source of heat gain/loss.
14. Consider using CO_2 sensors to reduce the amount of required fresh-air intake.
15. Consider using fireplaces only if they are supplied with outdoor combustion air, doors, and a heat exchanger. Consider wood-burning stoves instead, but use them only in rural areas.

APPENDIX A

Horizontal Sun-Path Diagrams

See Section 6.11 for a discussion of these horizontal sun-path diagrams.

For vertical sun-path diagrams see Appendix B, and for altitude and azimuth angles in tabular form see Appendix C.

All of these horizontal sun-path charts are for the Northern Hemisphere. However, it is easy to convert any of these charts for use in the Southern Hemisphere, as seen in Figure A.1.

STEPS FOR CONVERTING SUN-PATH CHARTS FOR USE IN THE SOUTHERN HEMISPHERE

1. Choose the chart for the latitude desired, and then reverse N and S as well as E and W.
2. Reverse the order of the months (e.g., June 21 and December 21 are interchanged).
3. Reverse the hours of the day (e.g., 2 P.M. and 10 A.M. are interchanged).

The charts for 24° to 52° are from *Architectural Graphic Standards*, 11th ed., published by the American Institute of Architects (AIA), John Wiley and Sons, 2007. Reprinted with permission of John Wiley & Sons, Inc. All other charts courtesy of Axel Jacobs, JALOXA Sunpath Diagrams, http://www.jaloxa.eu/resource/daylighting/sunpath.shtml.

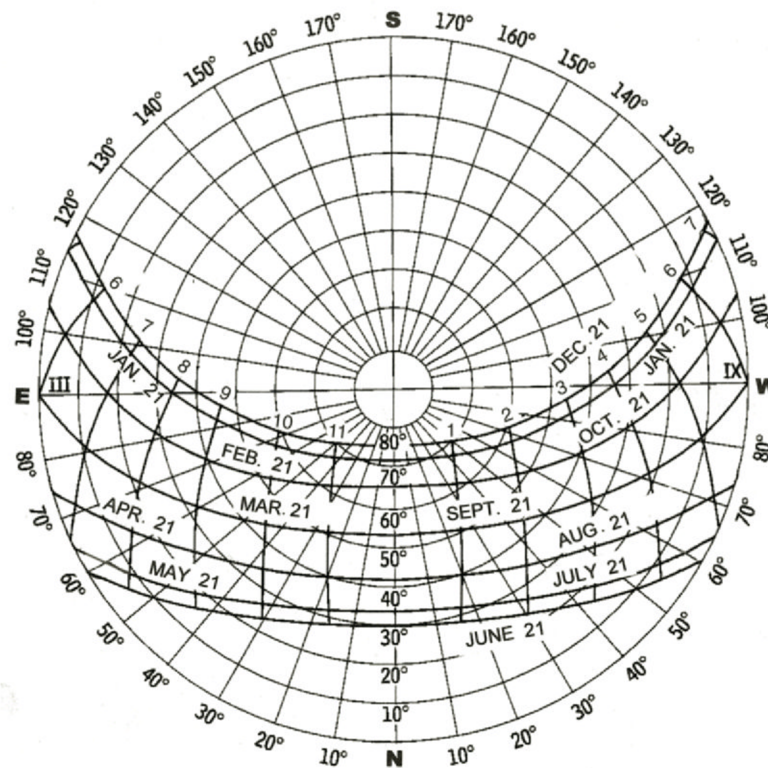
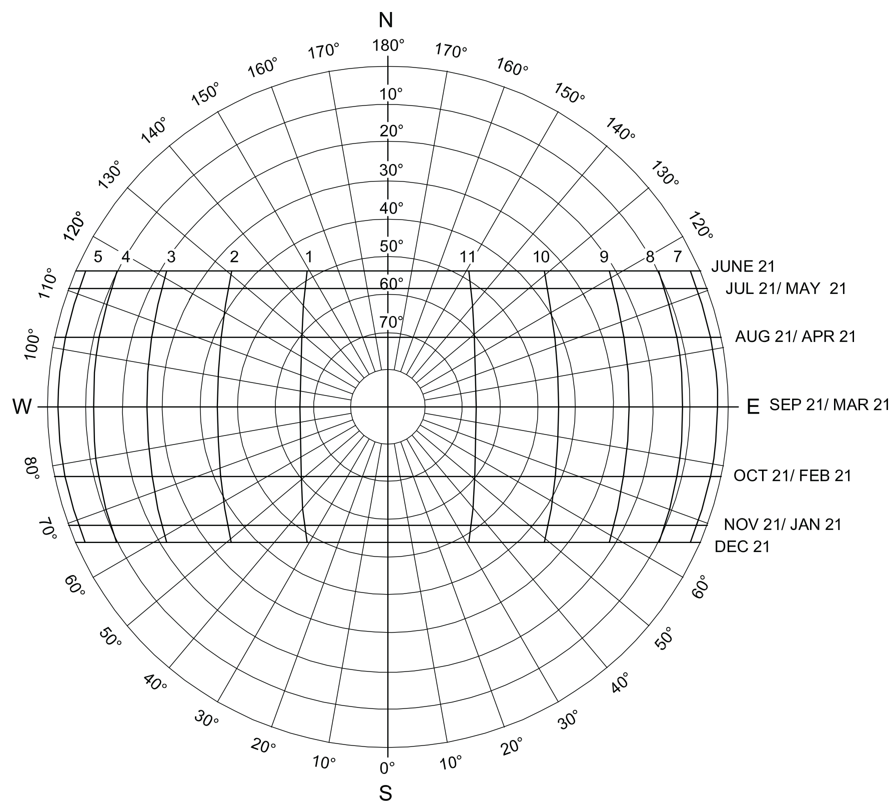
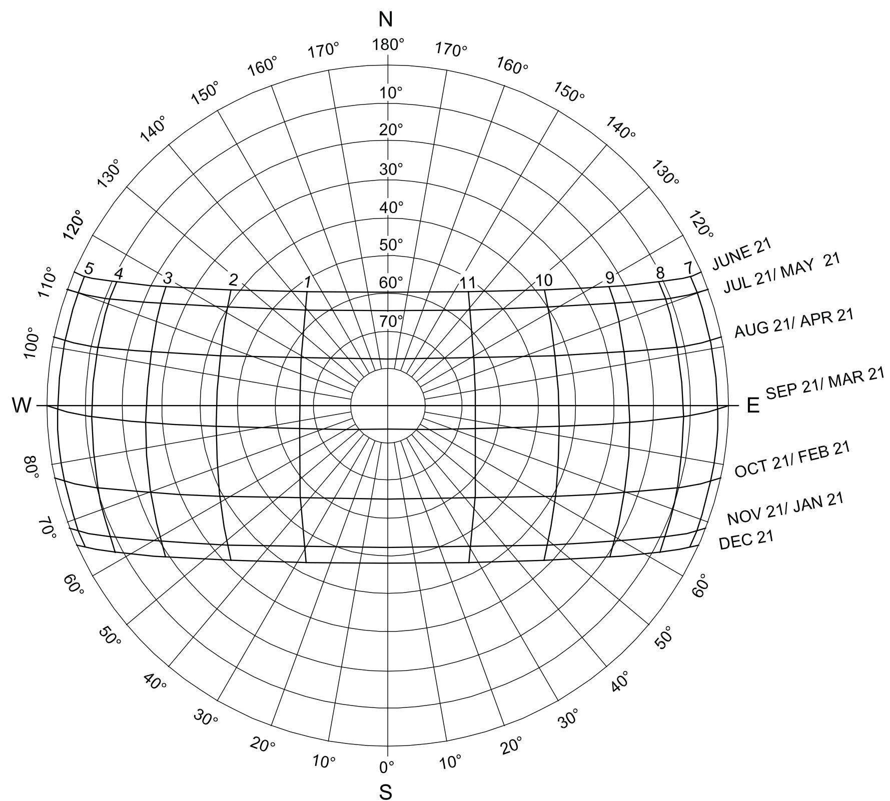


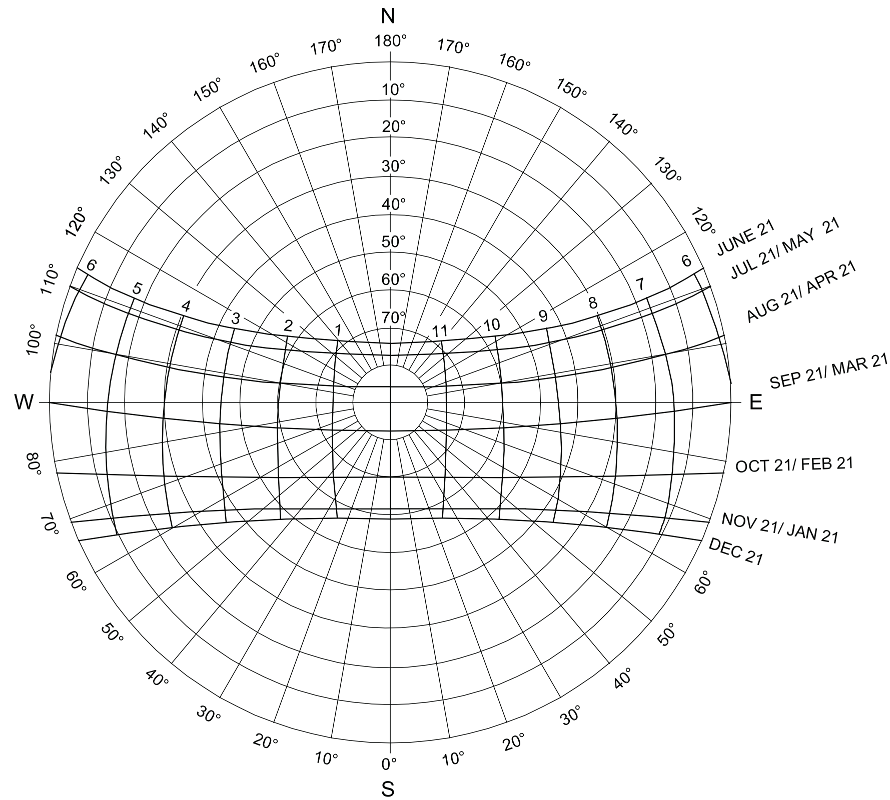
Figure A.1 This figure illustrates how to convert any of the Northern Hemisphere sun-path diagrams in this appendix into sun-path diagrams for the Southern Hemisphere.


N
S
W
E
JUNE 21
JUL 21/ MAY 21
AUG 21/ APR 21
SEP 21/ MAR 21
OCT 21/ FEB 21
NOV 21/ JAN 21
DEC 21

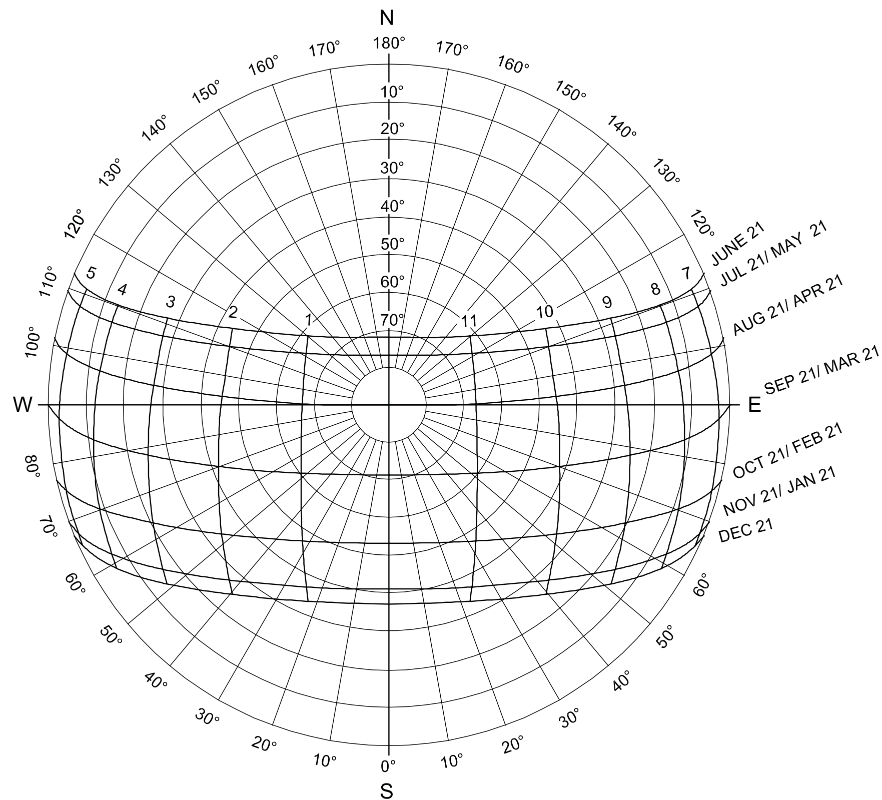
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N
S
W
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JUNE 21
JUL 21/ MAY 21
AUG 21/ APR 21
SEP 21/ MAR 21
OCT 21/ FEB 21
NOV 21/ JAN 21
DEC 21

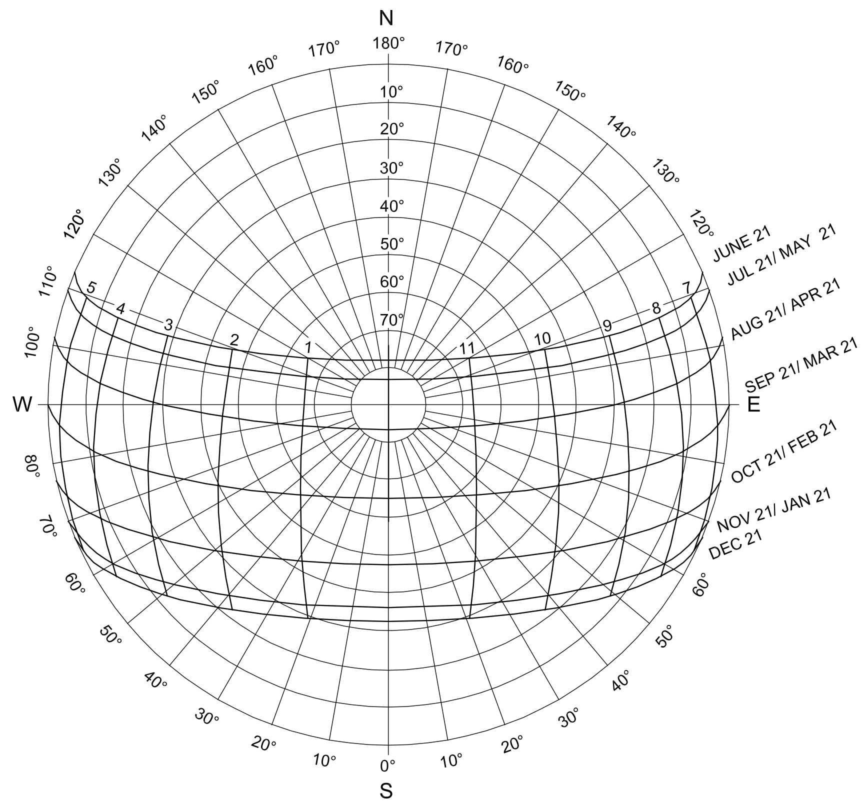
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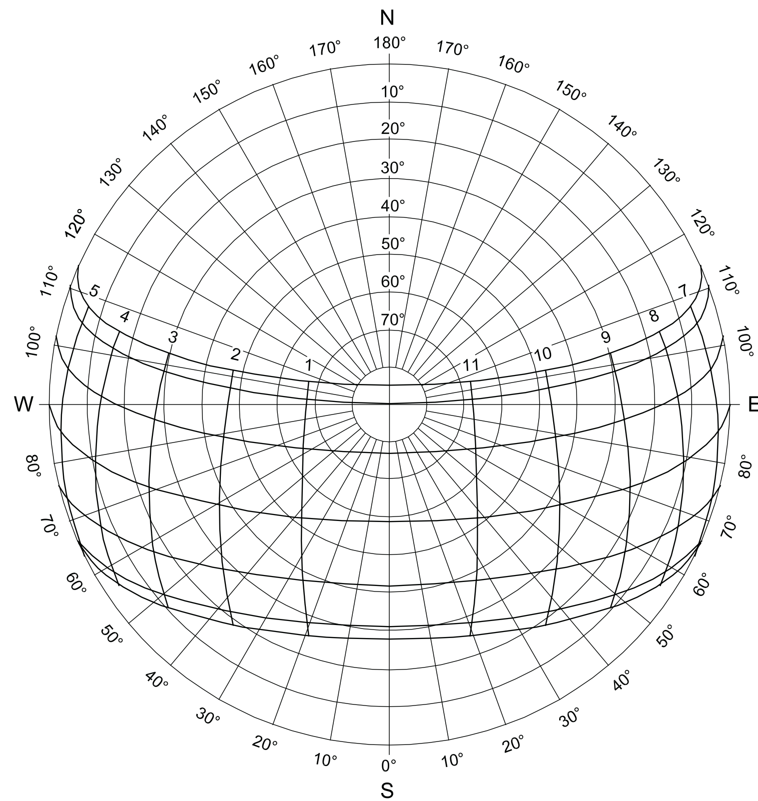
8° N LAT.



12° N LAT.

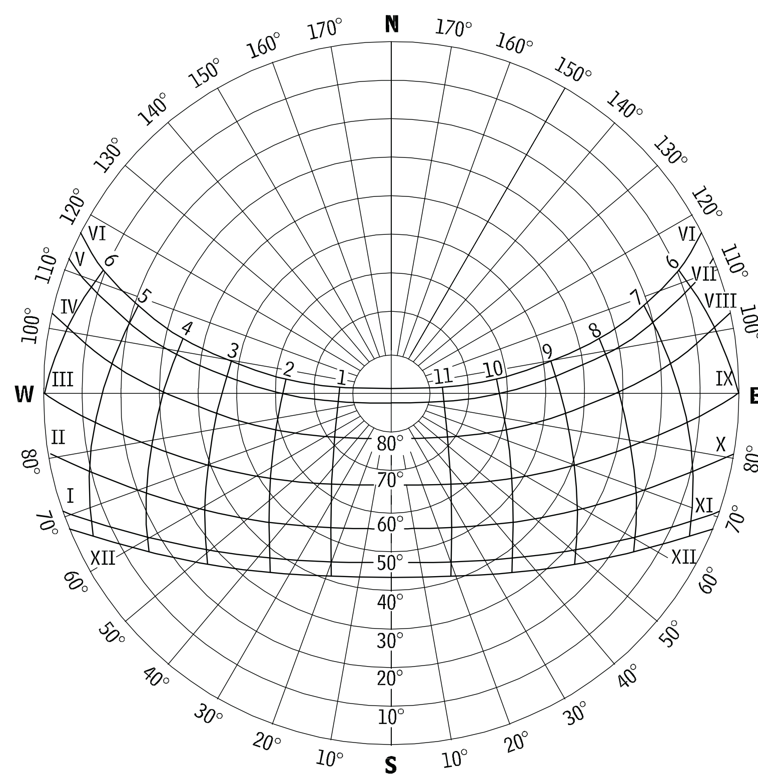


16° N LAT.

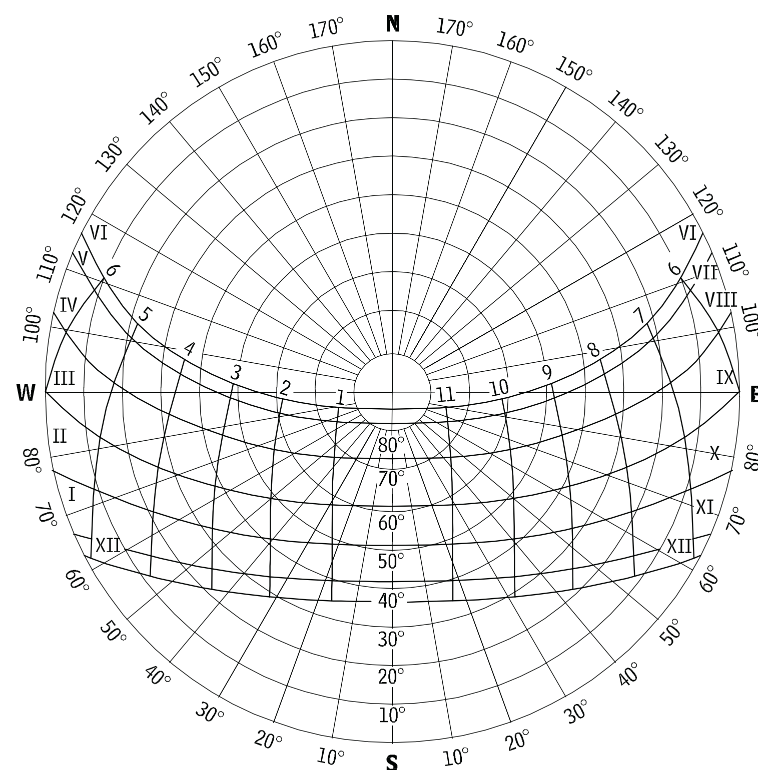


20° N LAT.

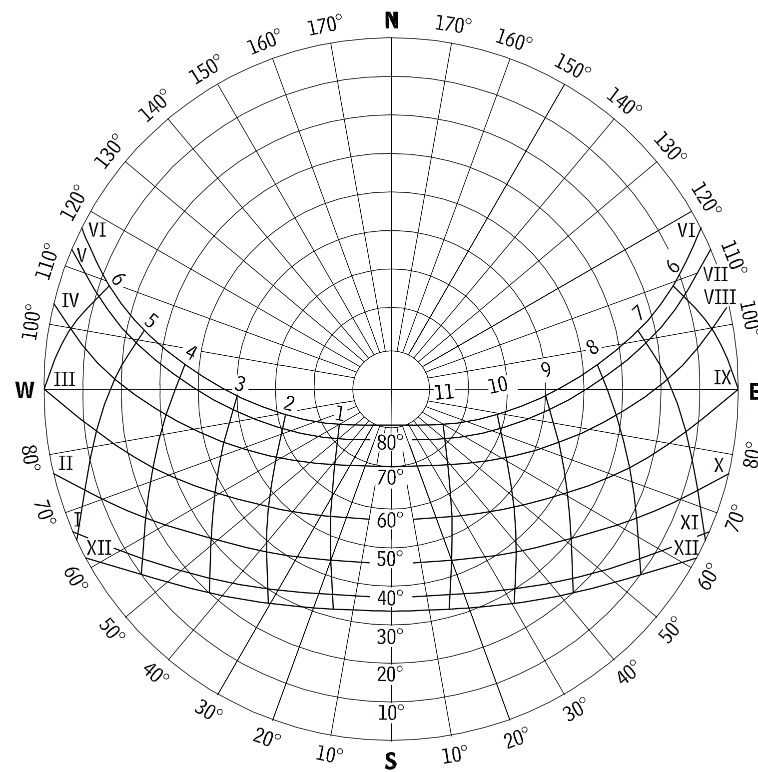
24° N LATITUDE
A.18



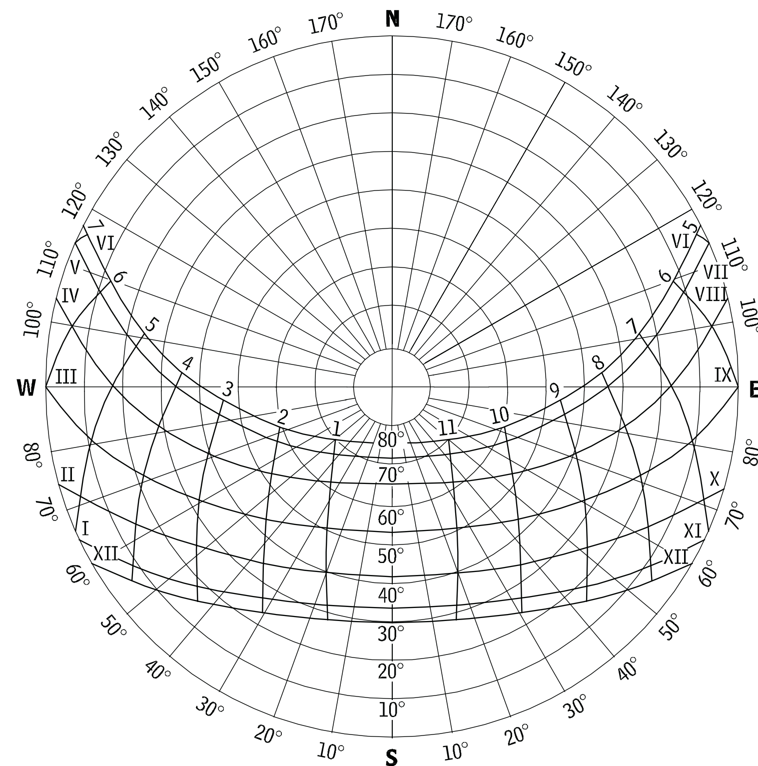
28° N LATITUDE
A.19



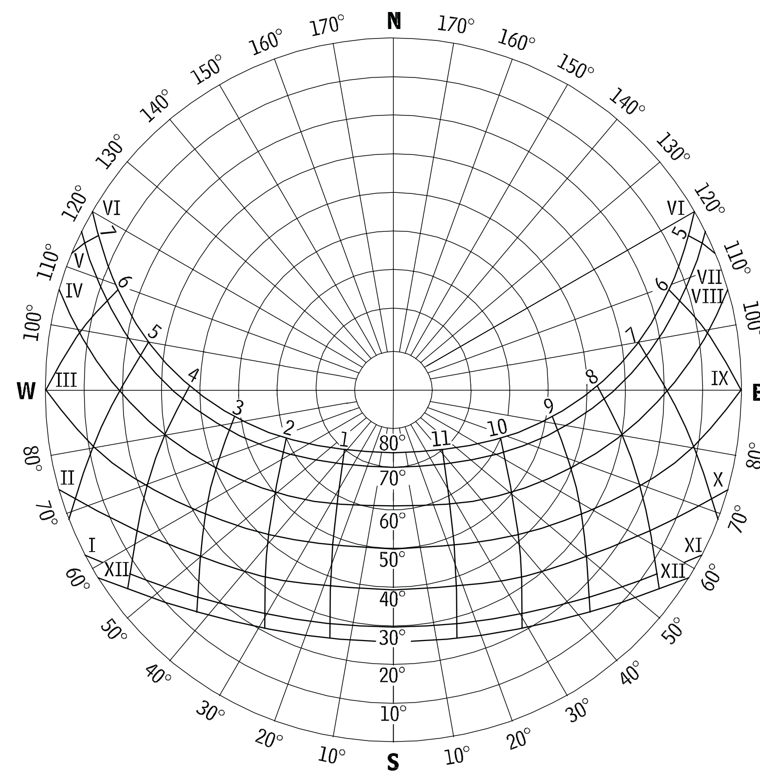
32° N LATITUDE
A.20



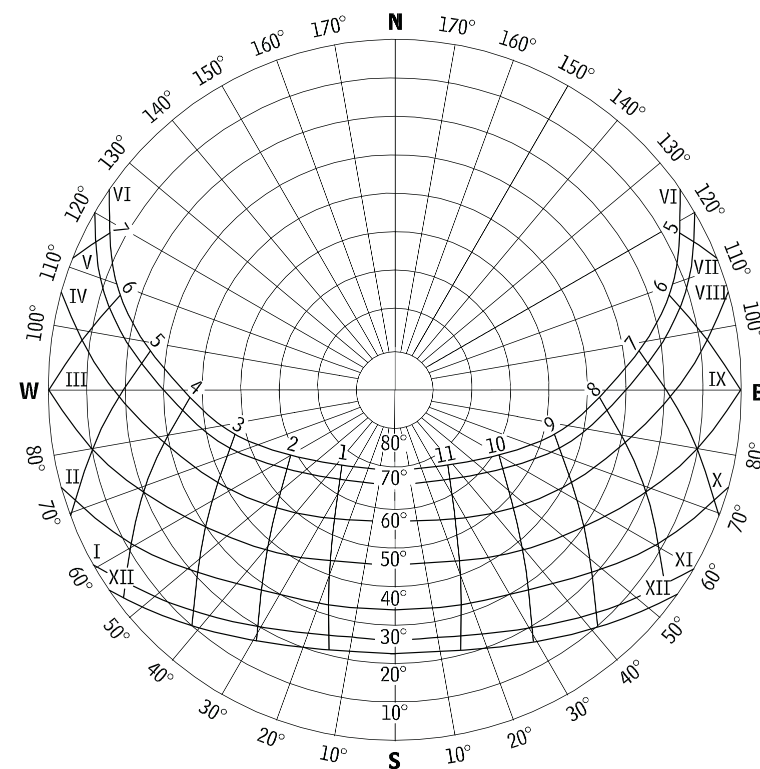
36° N LATITUDE
A.21



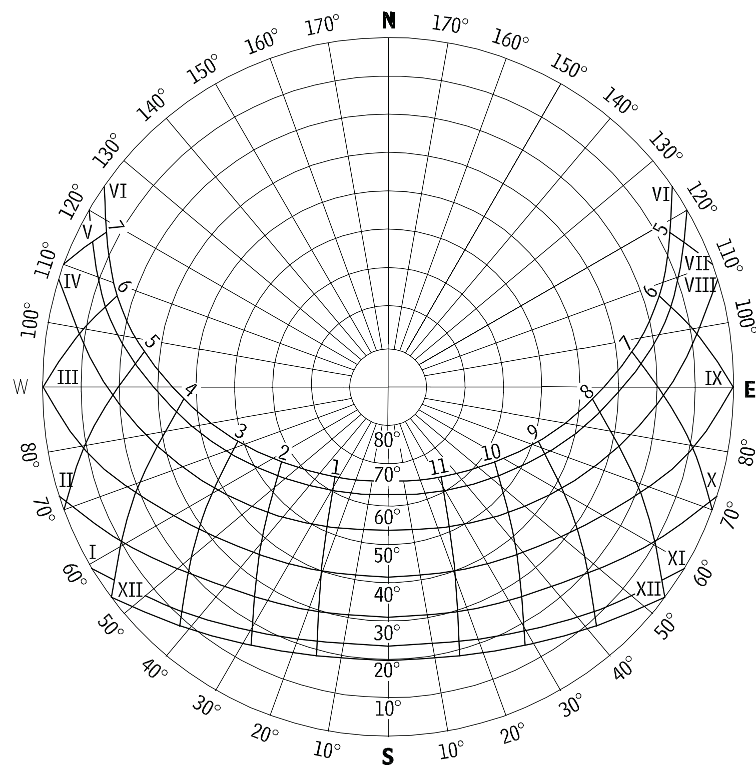
40° N LATITUDE
A.22



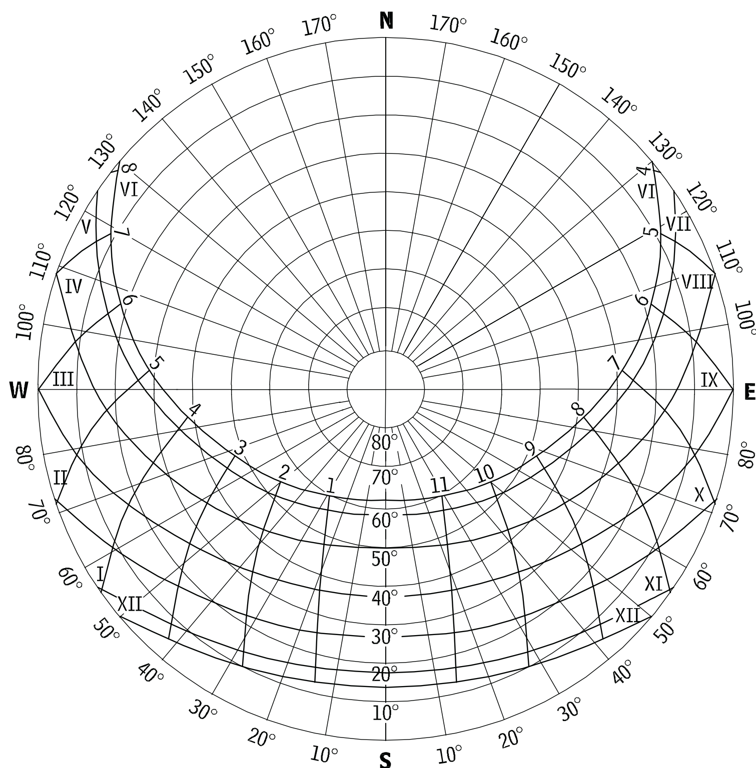
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A.23

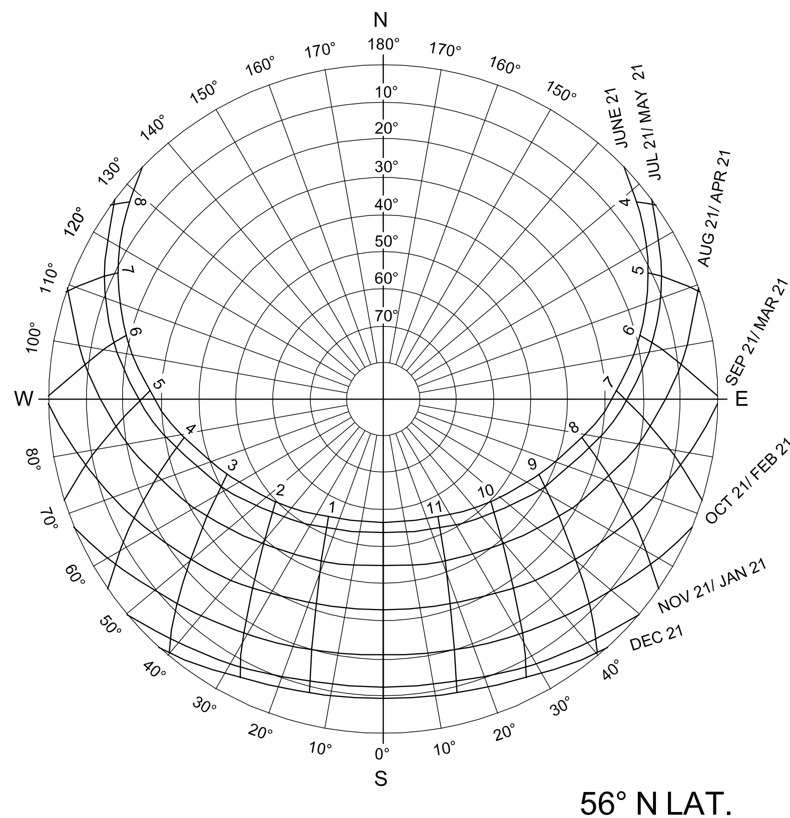


48° N LATITUDE
A.24

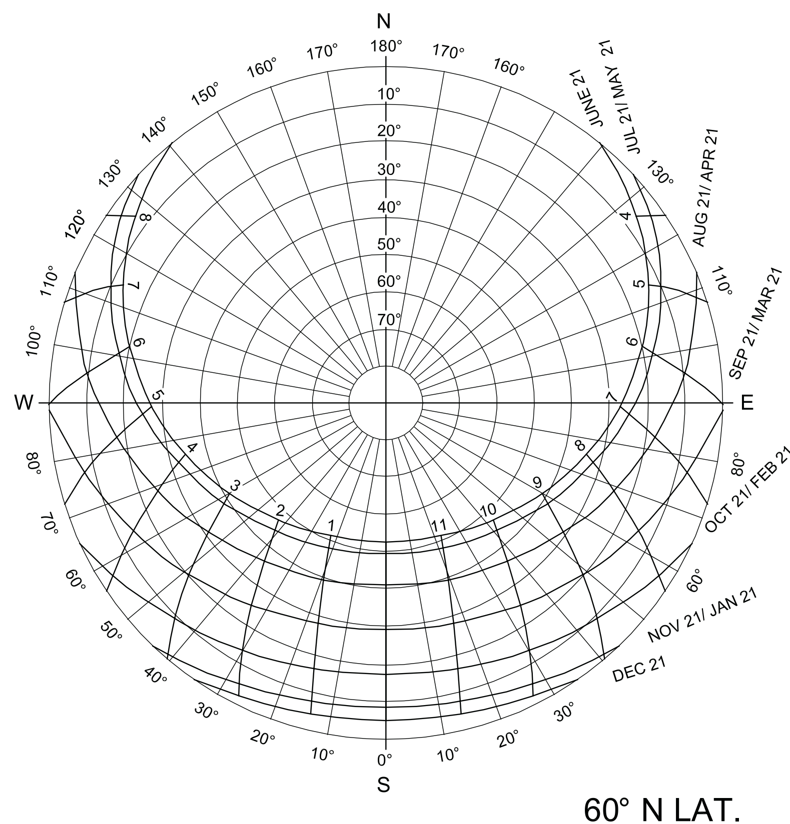


52° N LATITUDE
A.25

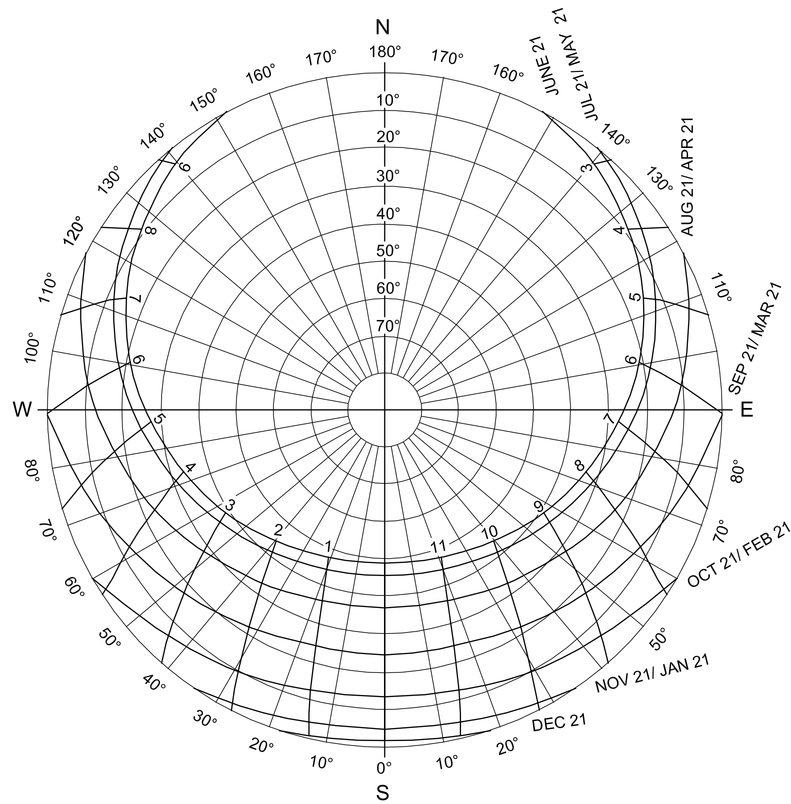




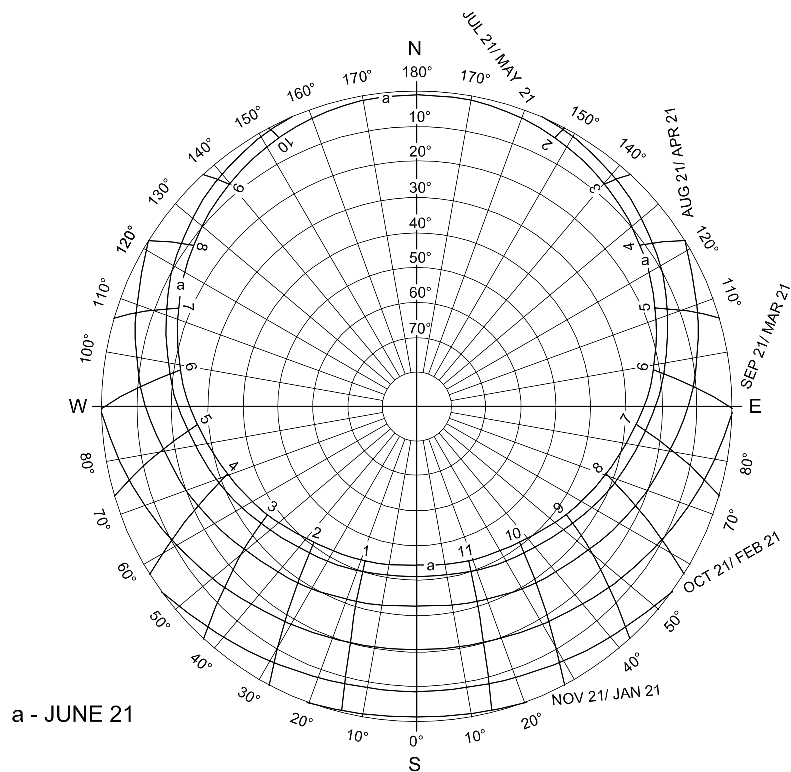
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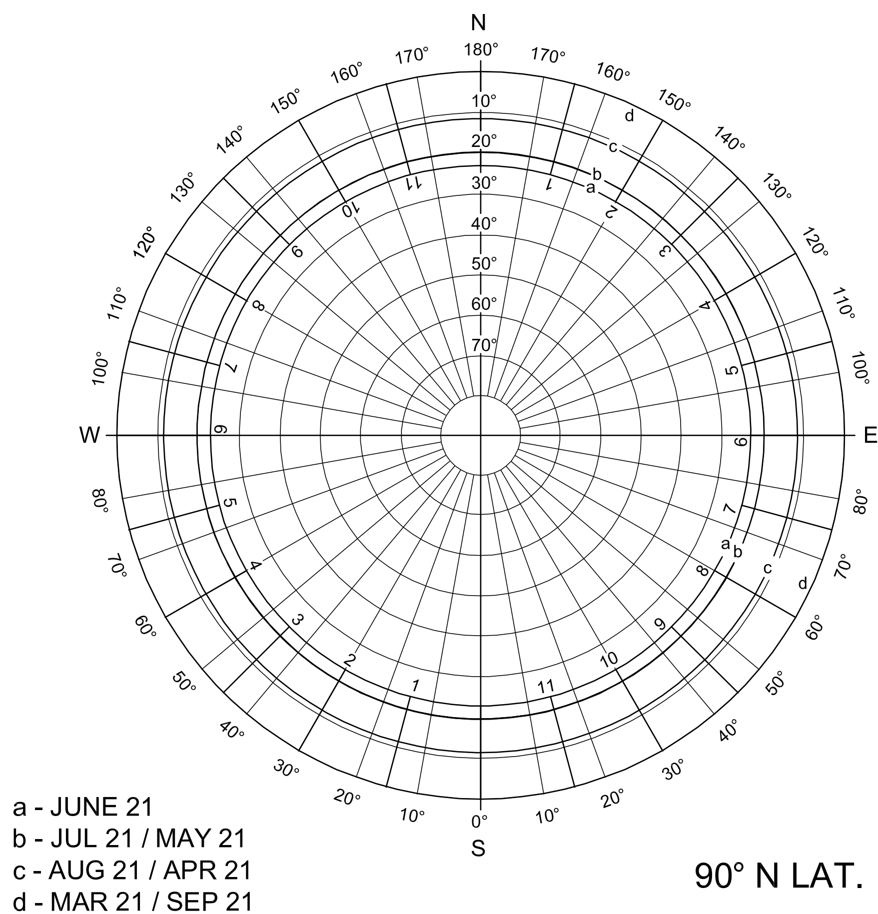
60° N LAT.



64° N LAT.



68° N LAT.


N
S
E
W
180°
0°
10°
20°
30°
40°
50°
60°
70°
a - JUNE 21
b - JUL 21 / MAY 21
c - AUG 21 / APR 21
d - MAR 21 / SEP 21
90° N LAT.

APPENDIX B

Vertical Sun-Path Diagrams

See Section 6.12 for a discussion of these vertical sun-path diagrams. All of the charts are for the Northern Hemisphere. However, it is easy to convert any of these charts for use in the Southern Hemisphere, as seen in Figure B.1.

STEPS FOR CONVERTING SUN-PATH CHARTS FOR USE IN THE SOUTHERN HEMISPHERE

1. Choose the chart for the latitude desired, and then reverse N and S as well as E and W.
2. Reverse the order of the months (e.g., June 21 and December 21 are interchanged).
3. Reverse the hours of the day (e.g., 2 P.M. and 10 A.M. are interchanged).

All of these vertical sun-path diagrams were generated with the sun-path chart program created by the University of Oregon Solar Radiation Monitoring Laboratory (www.solardata.uoregon.edu/SunChartProgram).*

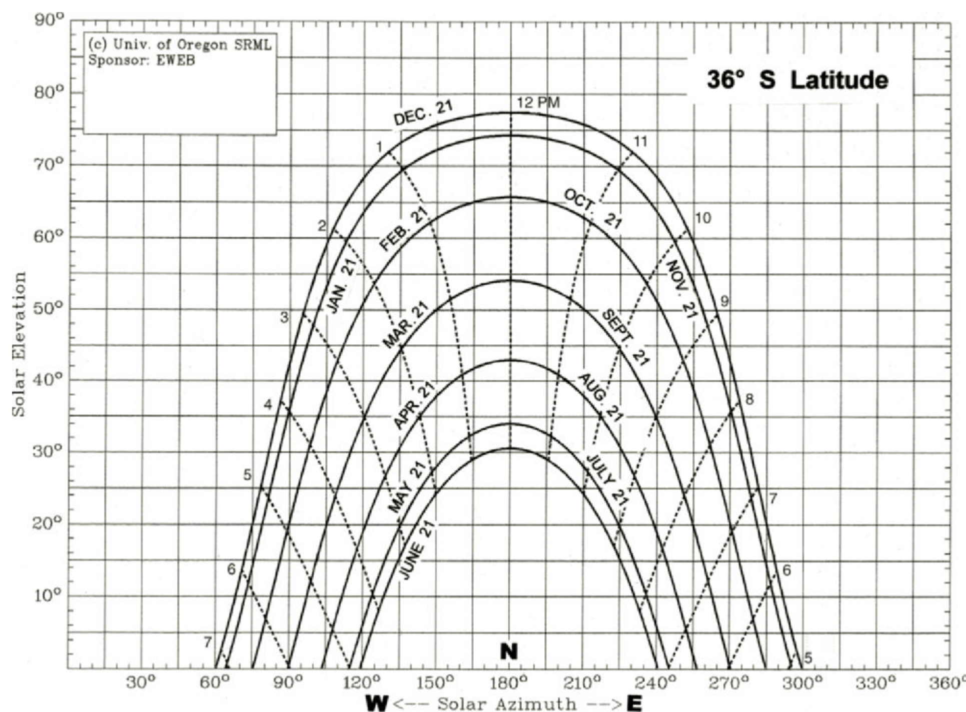
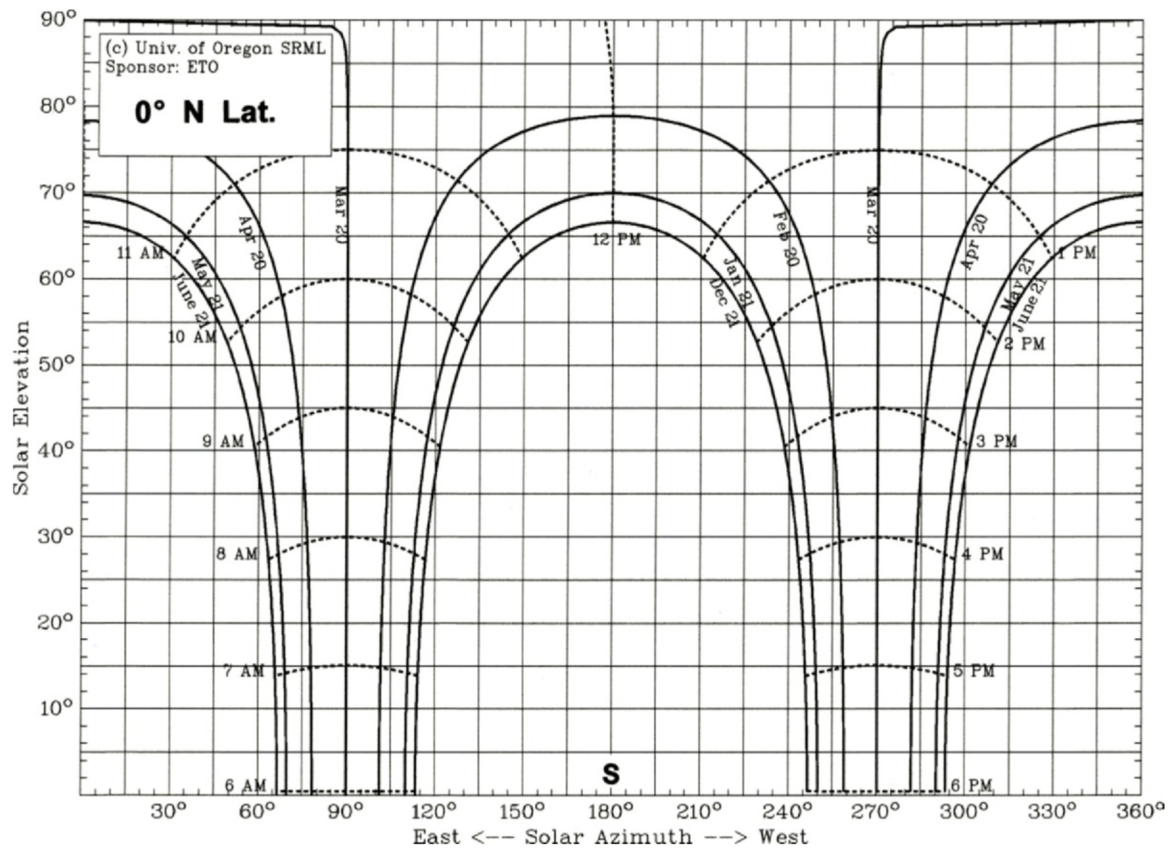
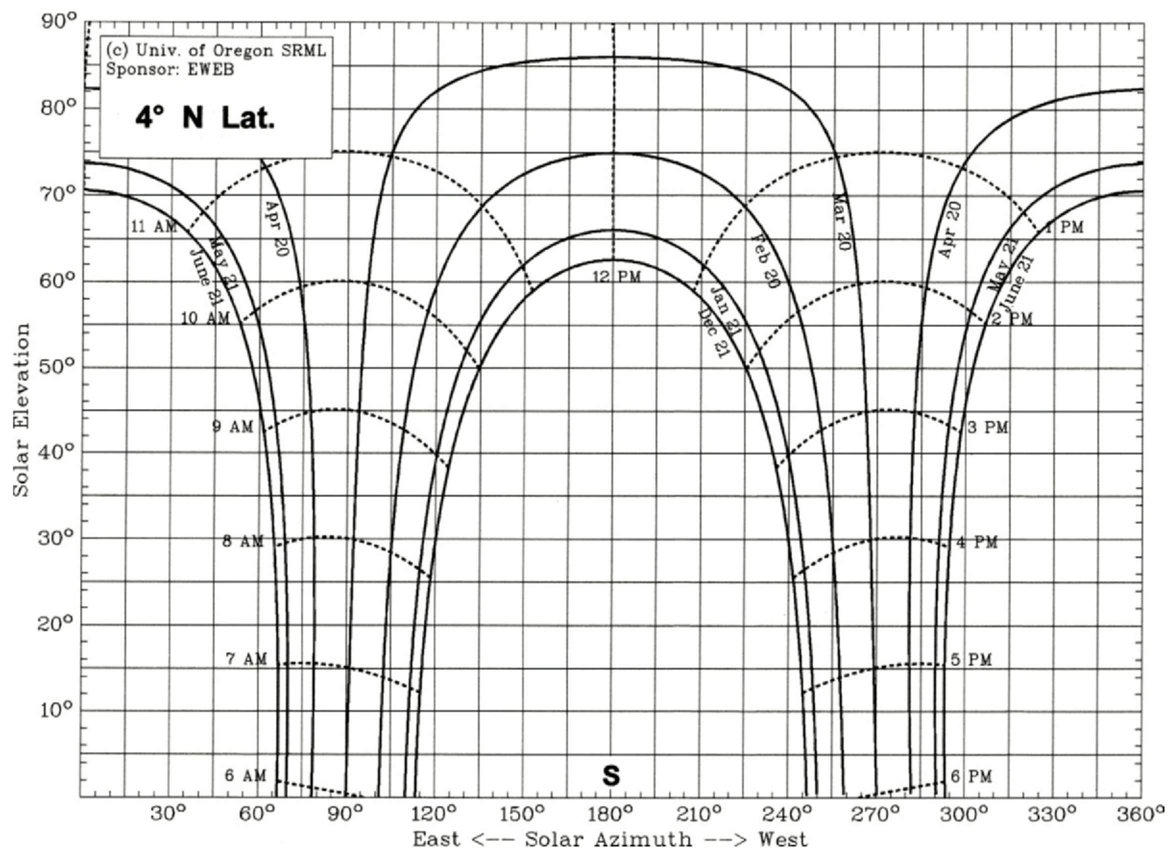
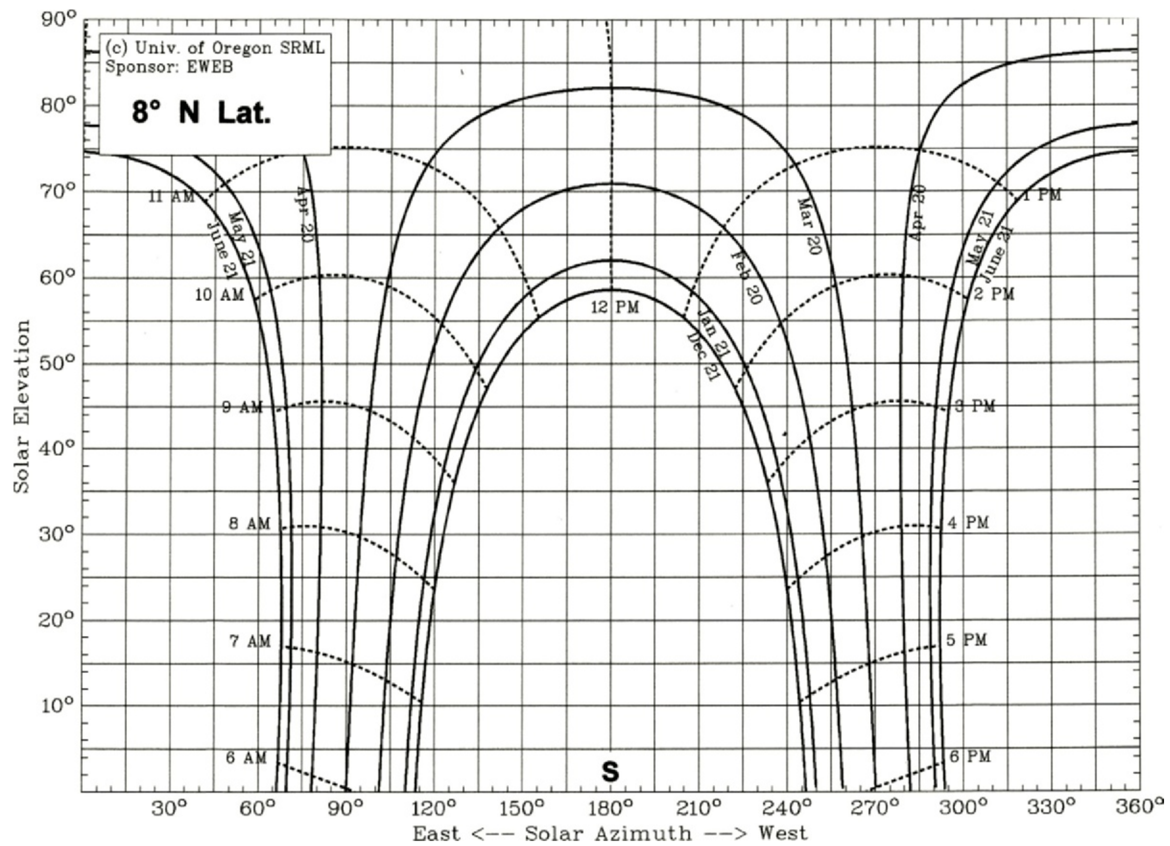


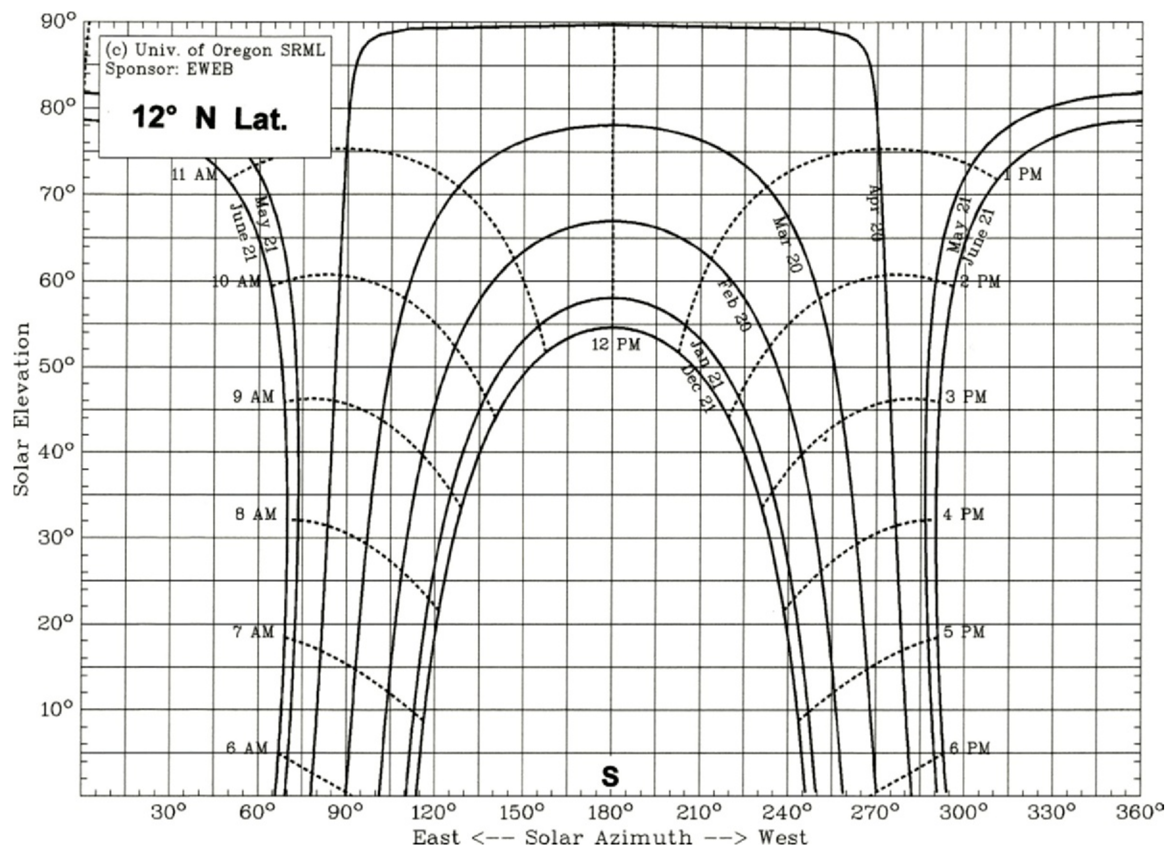
Figure B.1 This figure illustrates how to convert any of the Northern Hemisphere sun-path diagrams in this appendix into sun-path diagrams for the Southern Hemisphere.

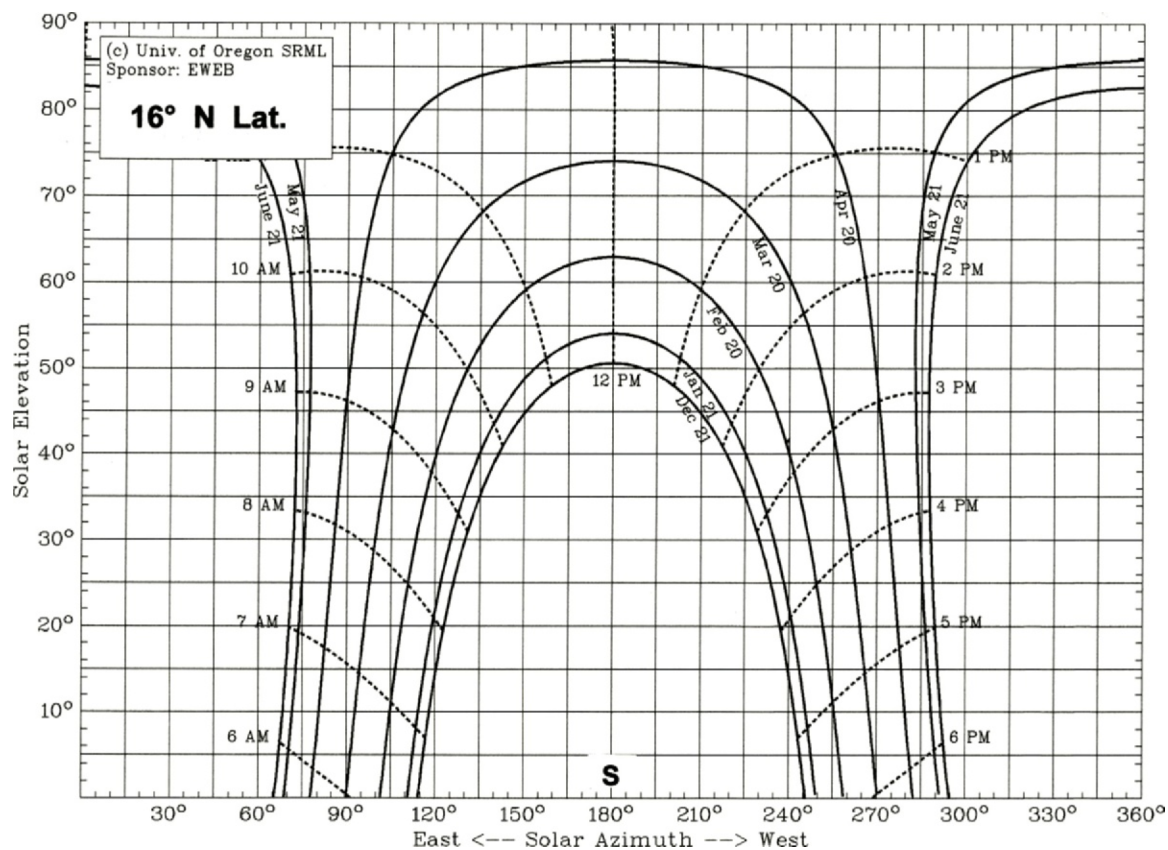
*Copyright 2003–2006, University of Oregon. All rights reserved. Created by Peter Harlan and Frank Vignola of the Solar Radiation Monitoring Laboratory.

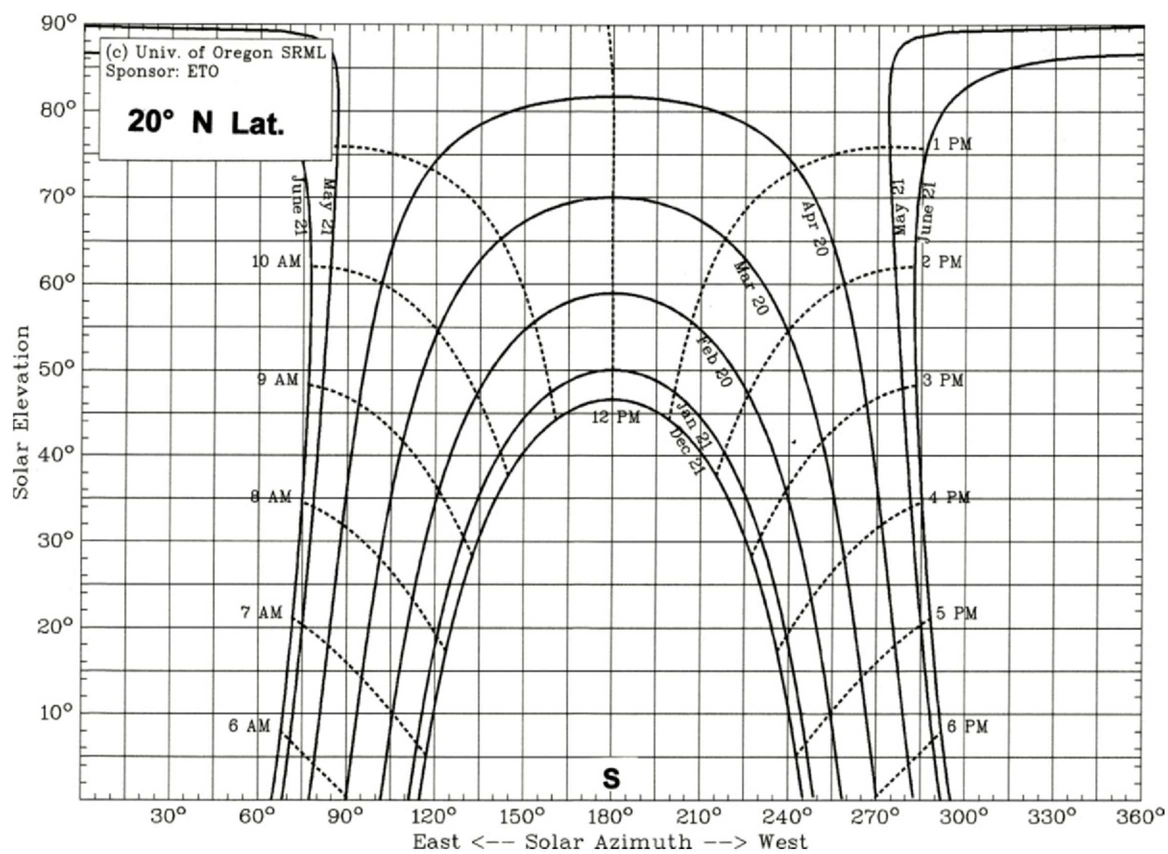

(c) Univ. of Oregon SRML
Sponsor: ETO
0° N Lat.
Solar Elevation
East <-- Solar Azimuth --> West
Mar 20
Apr 20
May 21
June 21
Feb 20
Jan 21
Dec 21
6 AM
7 AM
8 AM
9 AM
10 AM
11 AM
12 PM
1 PM
2 PM
3 PM
4 PM
5 PM
6 PM
S

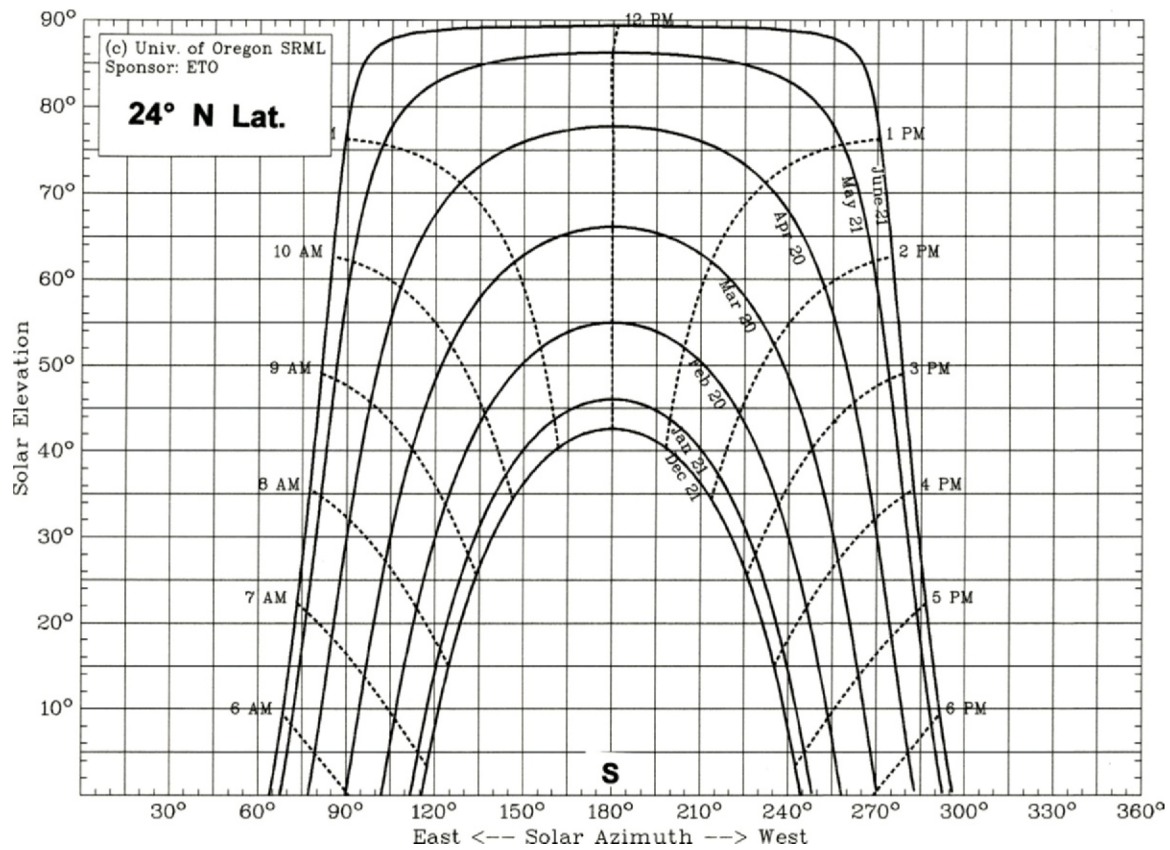

(c) Univ. of Oregon SRML
Sponsor: EWEB
4° N Lat.
Solar Elevation
East <-- Solar Azimuth --> West
Mar 20
Apr 20
May 21
June 21
Feb 20
Jan 21
Dec 21
6 AM
7 AM
8 AM
9 AM
10 AM
11 AM
12 PM
1 PM
2 PM
3 PM
4 PM
5 PM
6 PM
S

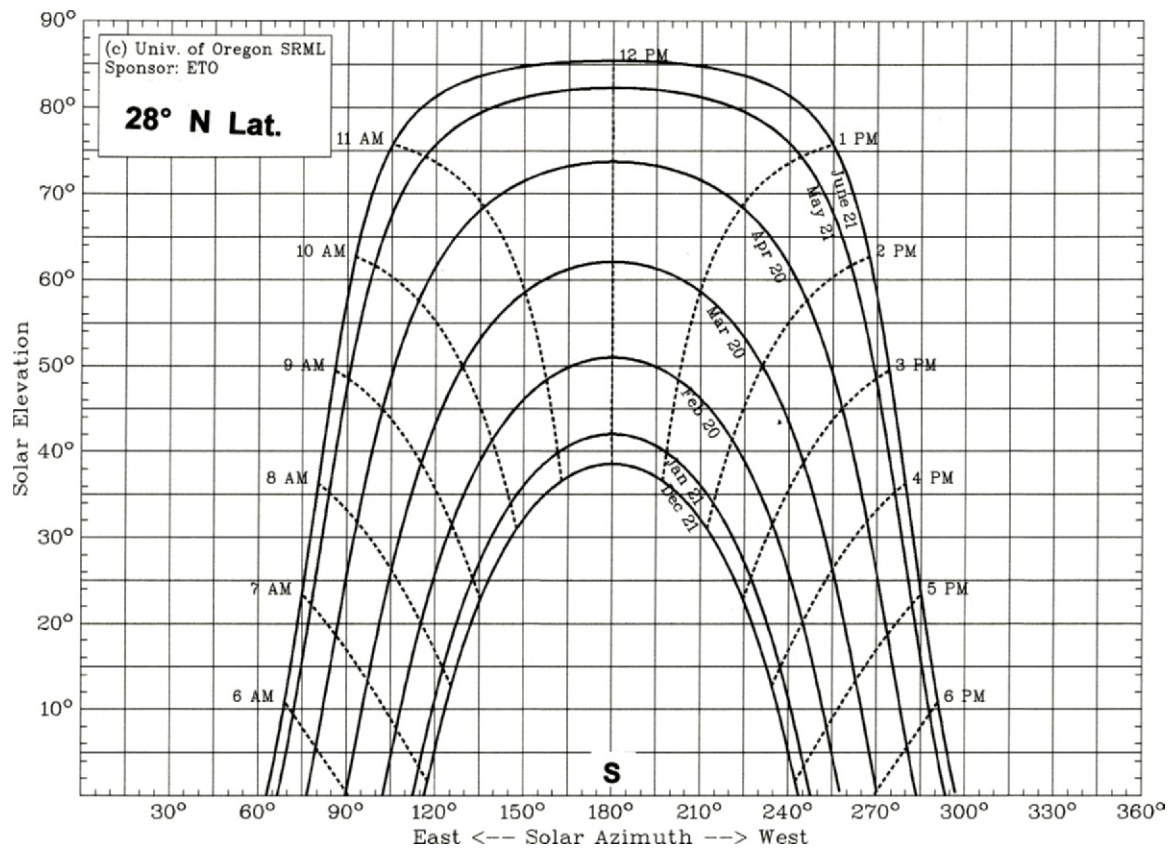

(c) Univ. of Oregon SRML
Sponsor: EWEB
8° N Lat.
Solar Elevation
East <-- Solar Azimuth --> West
S
12 PM
June 21
May 21
Apr 20
Mar 20
Feb 20
Jan 21
Dec 21
11 AM
10 AM
9 AM
8 AM
7 AM
6 AM
1 PM
2 PM
3 PM
4 PM
5 PM
6 PM

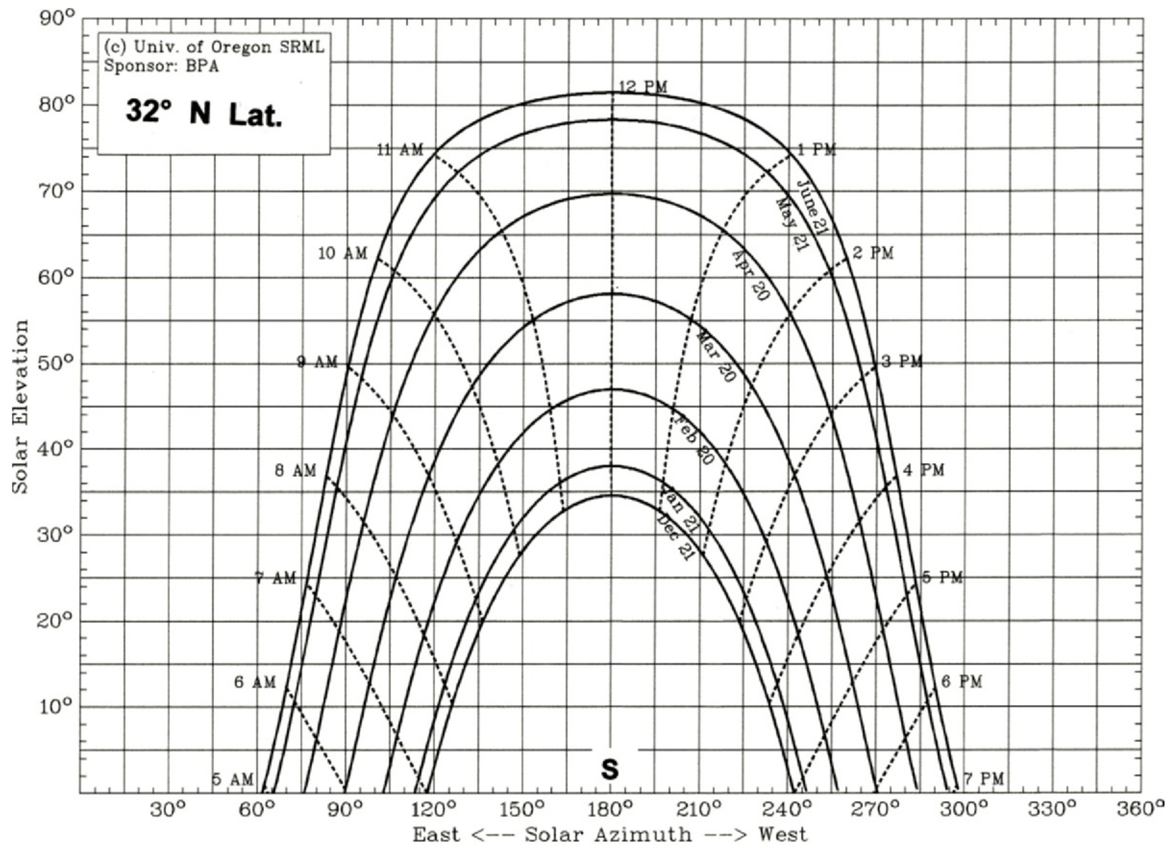

(c) Univ. of Oregon SRML
Sponsor: EWEB
12° N Lat.
Solar Elevation
East <-- Solar Azimuth --> West
S
12 PM
June 21
May 21
Apr 20
Mar 20
Feb 20
Jan 21
Dec 21
11 AM
10 AM
9 AM
8 AM
7 AM
6 AM
1 PM
2 PM
3 PM
4 PM
5 PM
6 PM

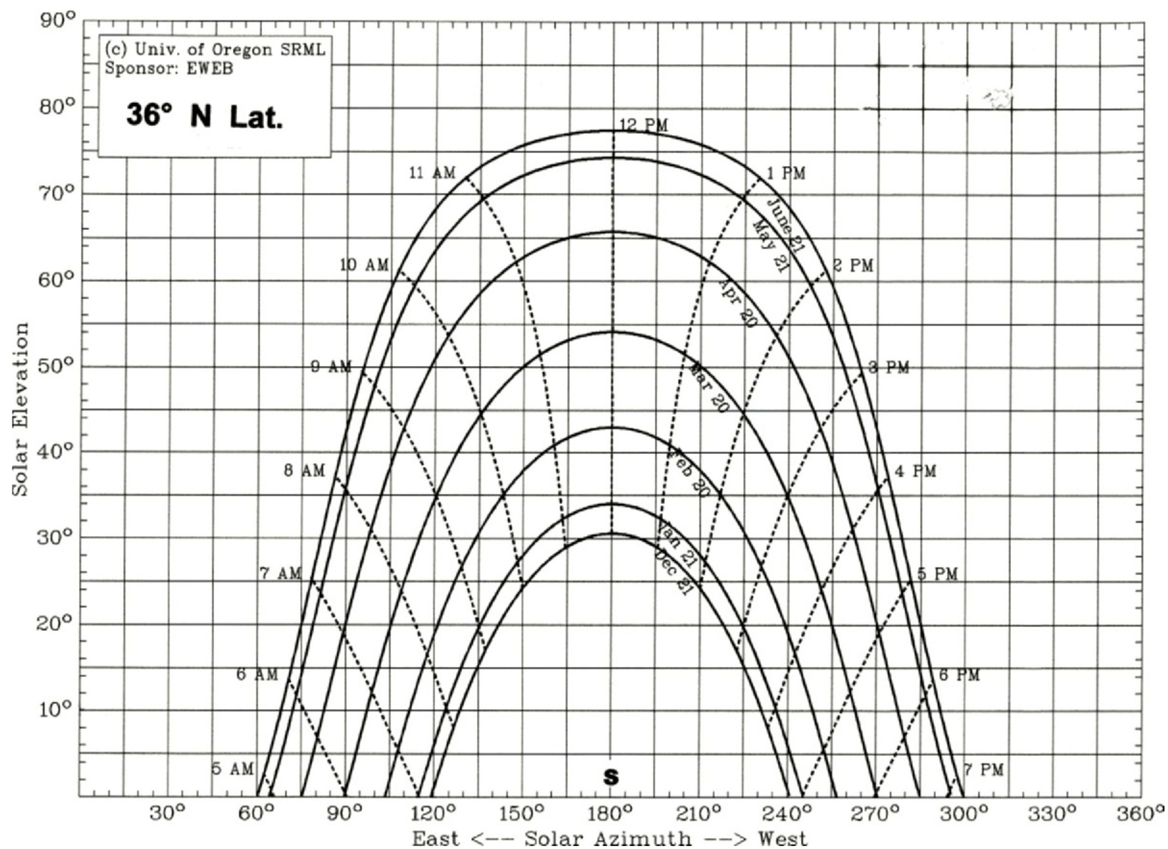

(c) Univ. of Oregon SRML
Sponsor: EWEB
16° N Lat.
Solar Elevation
East <-- Solar Azimuth --> West
S
12 PM
6 AM
7 AM
8 AM
9 AM
10 AM
1 PM
2 PM
3 PM
4 PM
5 PM
6 PM
June 21
May 21
Apr 20
Mar 20
Feb 20
Jan 21
Dec 21

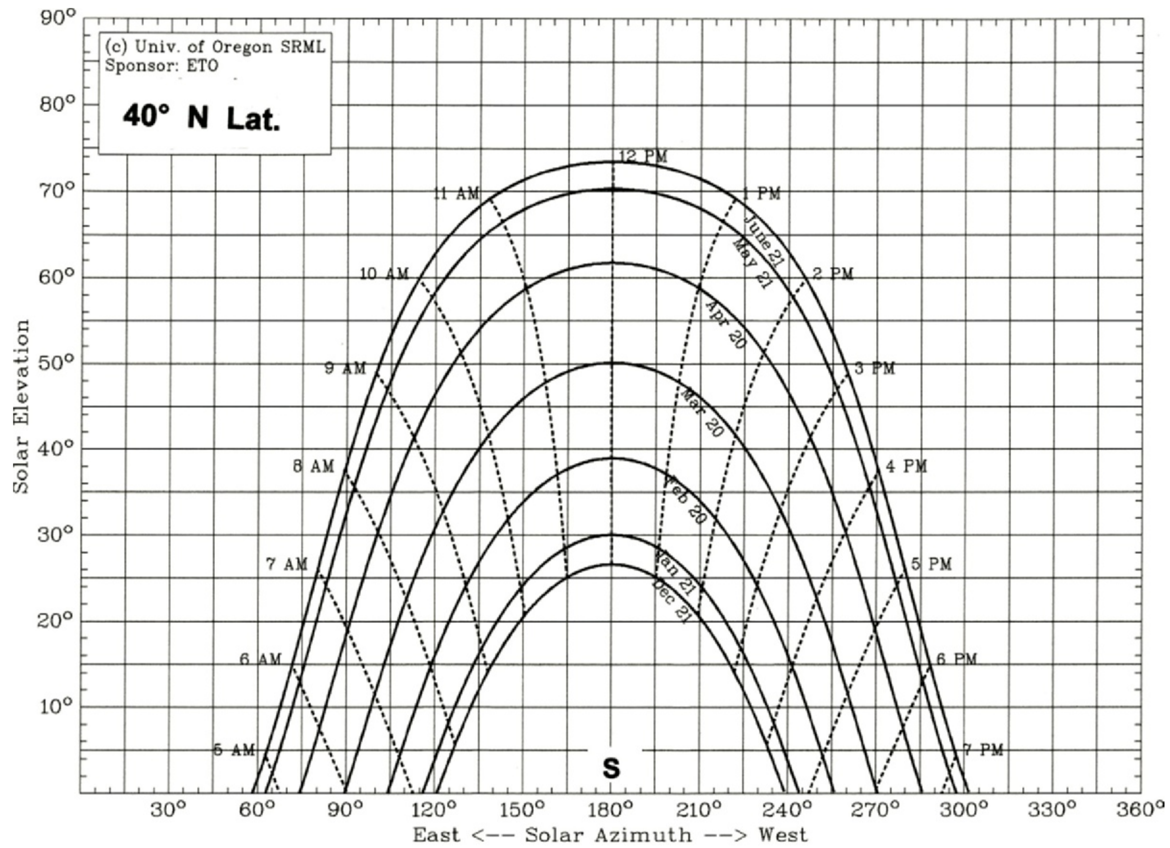

(c) Univ. of Oregon SRML
Sponsor: ETO
20° N Lat.
Solar Elevation
East <-- Solar Azimuth --> West
S
12 PM
6 AM
7 AM
8 AM
9 AM
10 AM
1 PM
2 PM
3 PM
4 PM
5 PM
6 PM
June 21
May 21
Apr 20
Mar 20
Feb 20
Jan 21
Dec 21

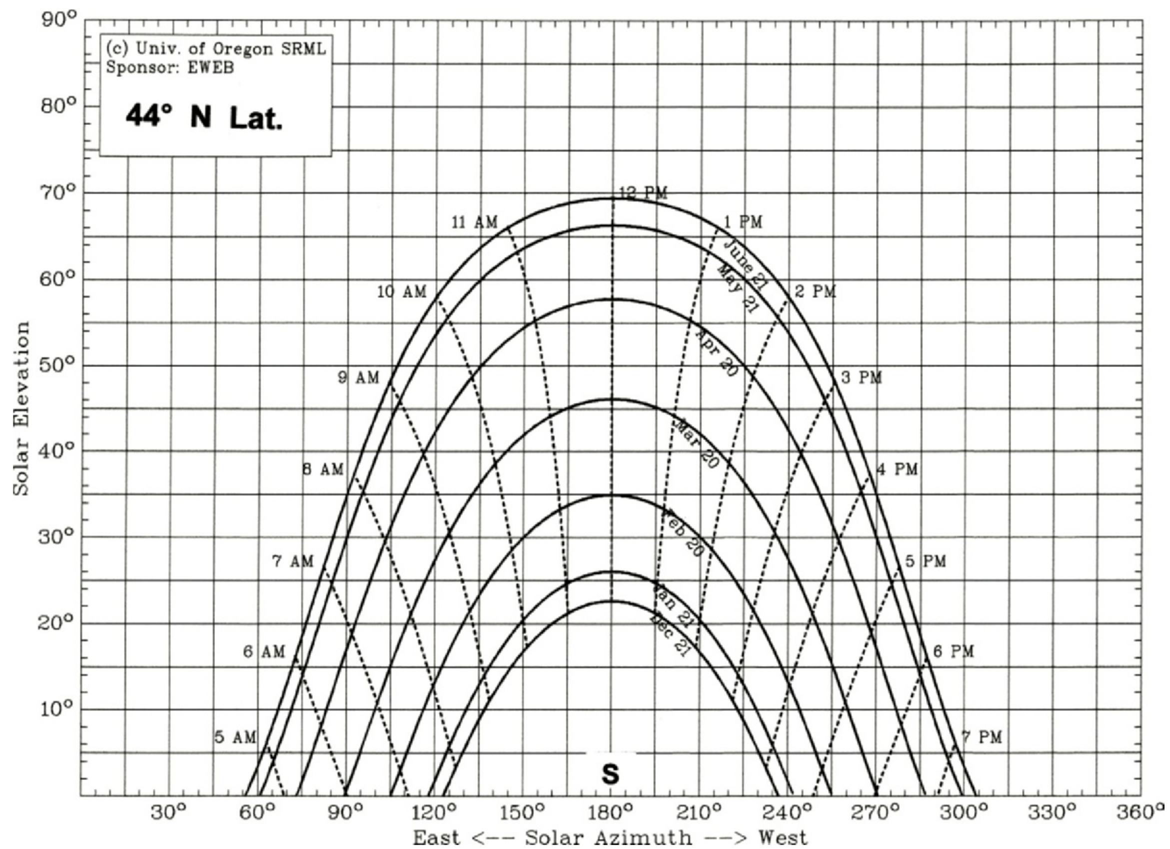

(c) Univ. of Oregon SRML
Sponsor: ETO
24° N Lat.
Solar Elevation
East <-- Solar Azimuth --> West
12 PM
1 PM
10 AM
2 PM
9 AM
3 PM
8 AM
4 PM
7 AM
5 PM
6 AM
6 PM
June 21
May 21
Apr 20
Mar 20
Feb 20
Jan 21
Dec 21
S
90°
80°
70°
60°
50°
40°
30°
20°
10°
30°
60°
90°
120°
150°
180°
210°
240°
270°
300°
330°
360°

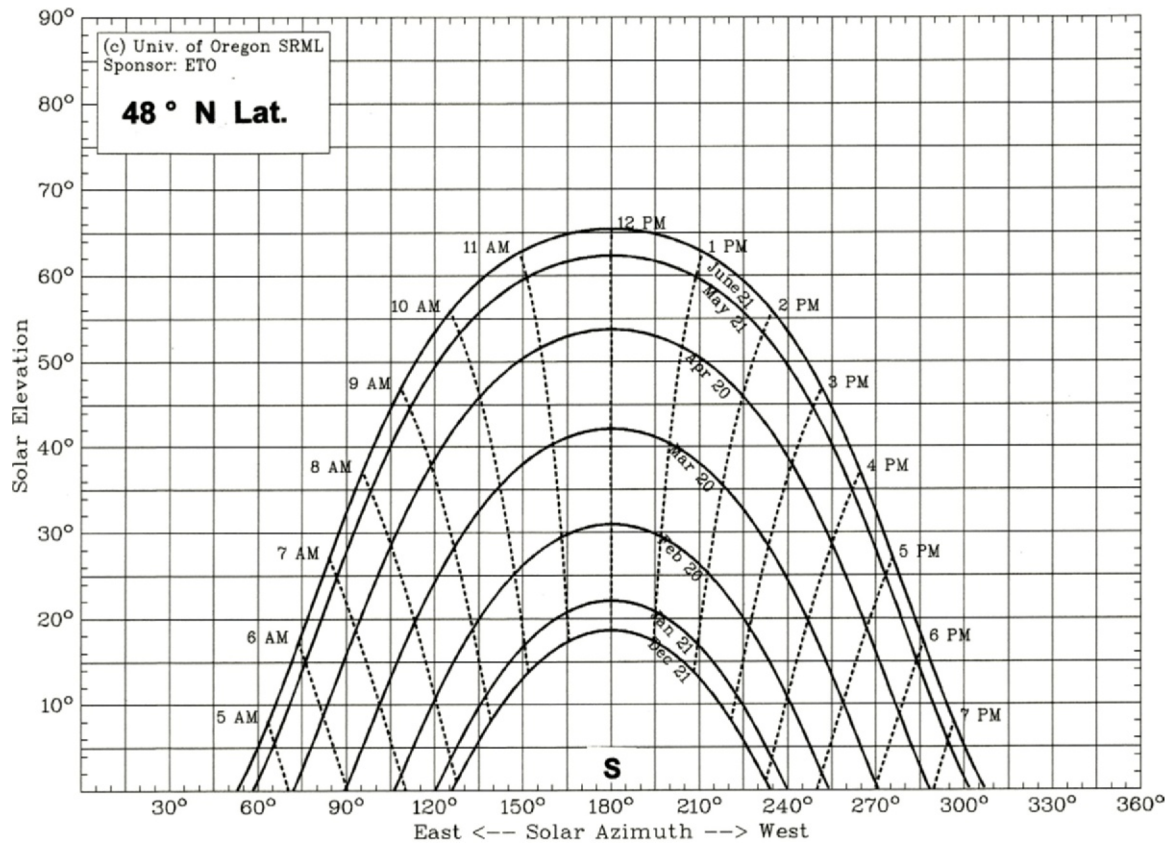

(c) Univ. of Oregon SRML
Sponsor: ETO
28° N Lat.
Solar Elevation
East <-- Solar Azimuth --> West
12 PM
11 AM
1 PM
10 AM
2 PM
9 AM
3 PM
8 AM
4 PM
7 AM
5 PM
6 AM
6 PM
June 21
May 21
Apr 20
Mar 20
Feb 20
Jan 21
Dec 21
S
90°
80°
70°
60°
50°
40°
30°
20°
10°
30°
60°
90°
120°
150°
180°
210°
240°
270°
300°
330°
360°

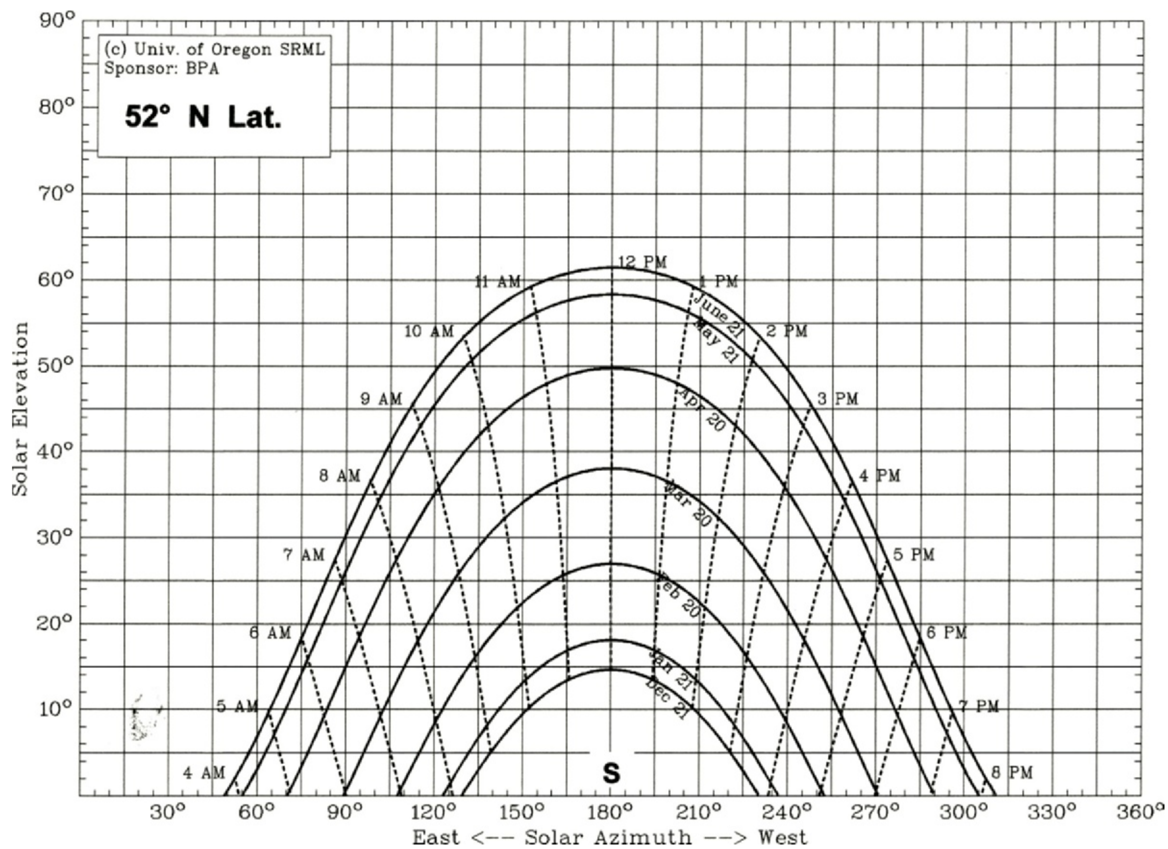

(c) Univ. of Oregon SRML
Sponsor: BPA
32° N Lat.
Solar Elevation
East <-- Solar Azimuth --> West
12 PM
11 AM
1 PM
10 AM
2 PM
9 AM
3 PM
8 AM
4 PM
7 AM
5 PM
6 AM
6 PM
5 AM
7 PM
June 21
May 21
Apr 20
Mar 20
Feb 20
Jan 21
Dec 21
S

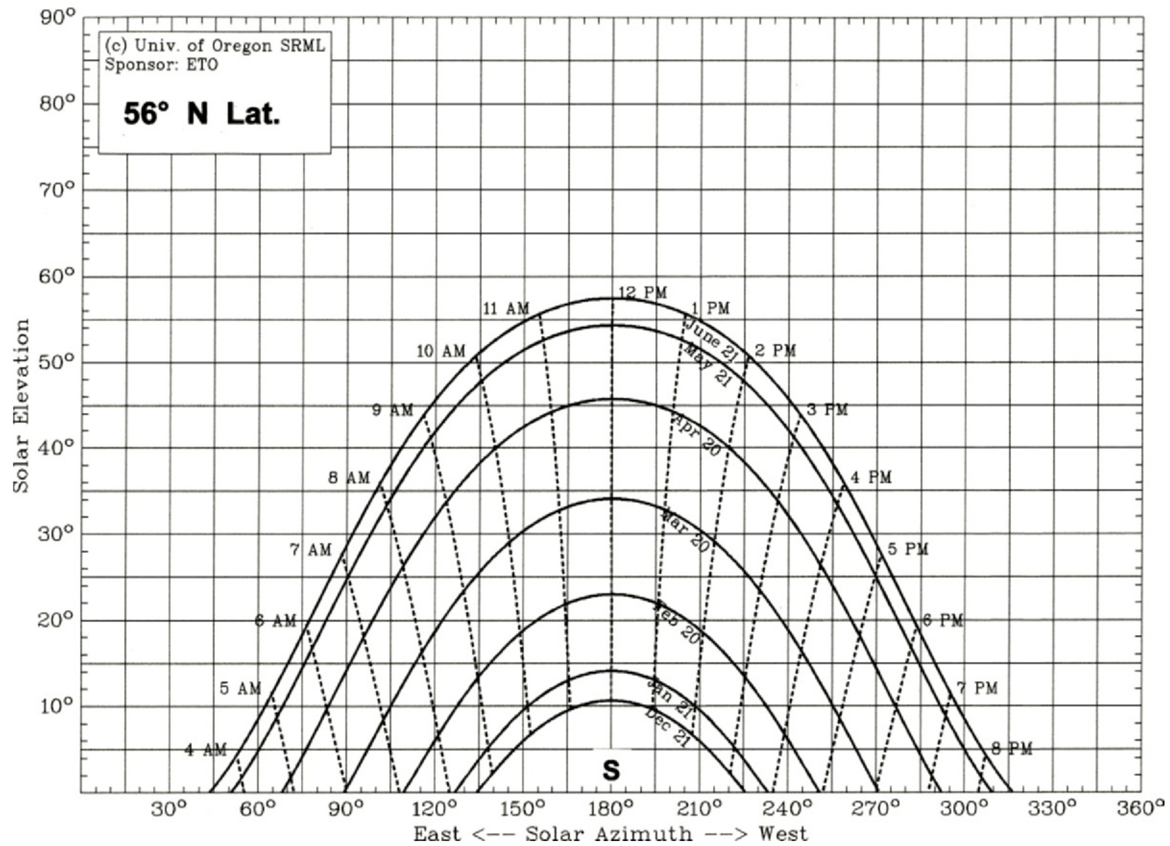

(c) Univ. of Oregon SRML
Sponsor: EWEB
36° N Lat.
Solar Elevation
East <-- Solar Azimuth --> West
12 PM
11 AM
1 PM
10 AM
2 PM
9 AM
3 PM
8 AM
4 PM
7 AM
5 PM
6 AM
6 PM
5 AM
7 PM
June 21
May 21
Apr 20
Mar 20
Feb 20
Jan 21
Dec 21
S

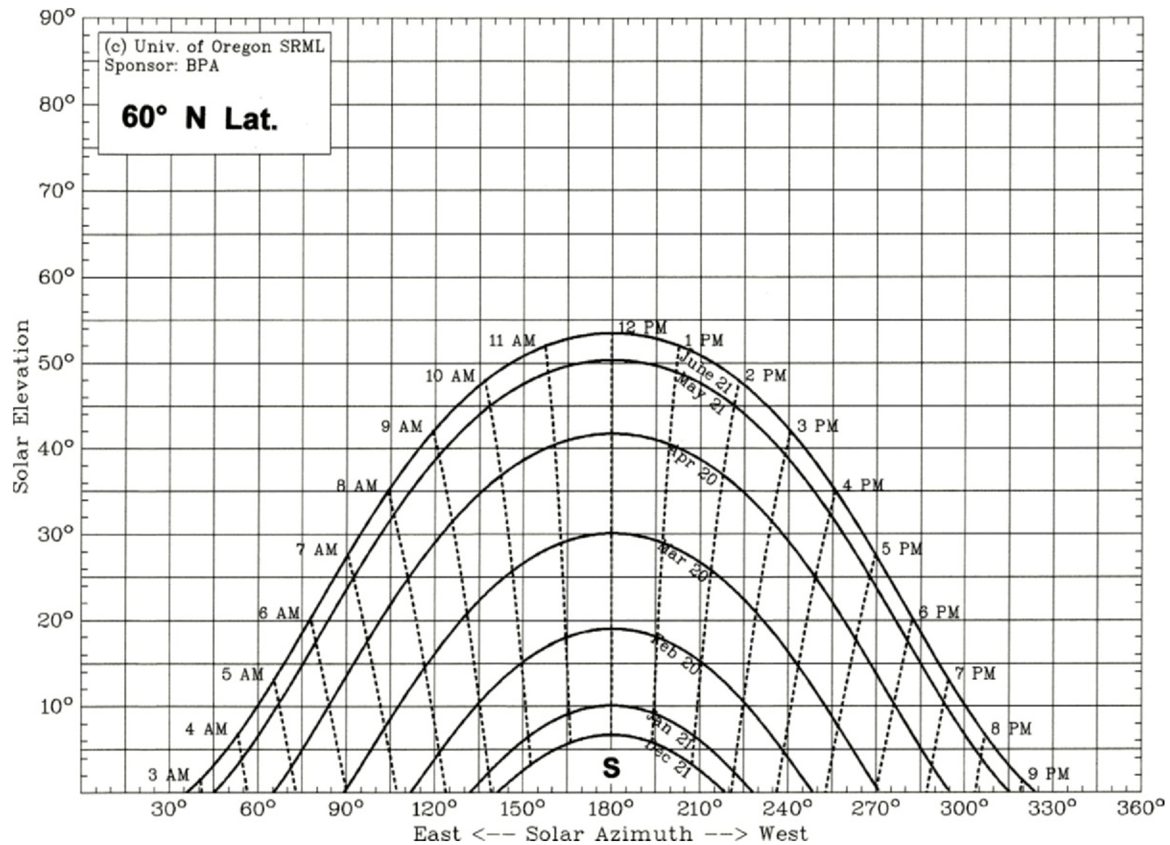

(c) Univ. of Oregon SRML
Sponsor: ETO
40° N Lat.
Solar Elevation
East <-- Solar Azimuth --> West
S
12 PM
11 AM
1 PM
10 AM
2 PM
9 AM
3 PM
8 AM
4 PM
7 AM
5 PM
6 AM
6 PM
5 AM
7 PM
June 21
May 21
Apr 20
Mar 20
Feb 20
Jan 21
Dec 21

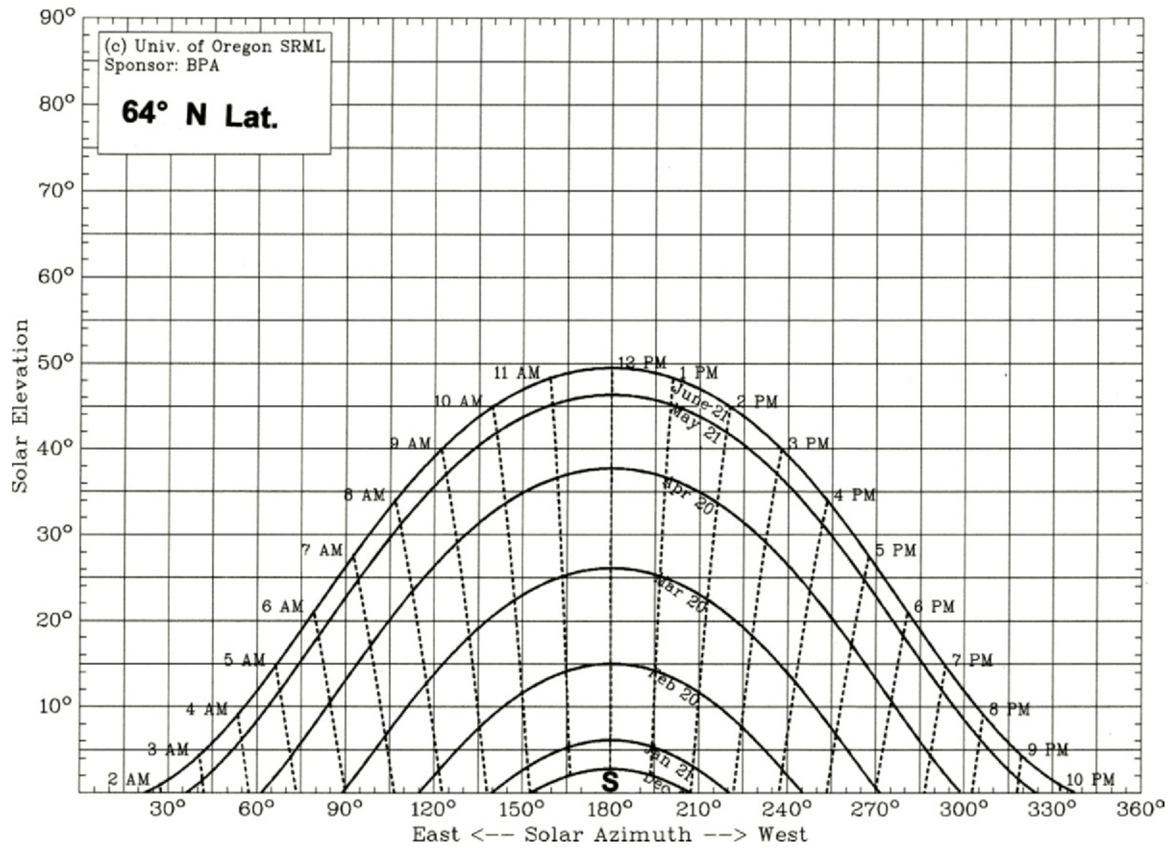

(c) Univ. of Oregon SRML
Sponsor: EWEB
44° N Lat.
Solar Elevation
East <-- Solar Azimuth --> West
S
12 PM
11 AM
1 PM
10 AM
2 PM
9 AM
3 PM
8 AM
4 PM
7 AM
5 PM
6 AM
6 PM
5 AM
7 PM
June 21
May 21
Apr 20
Mar 20
Feb 20
Jan 21
Dec 21

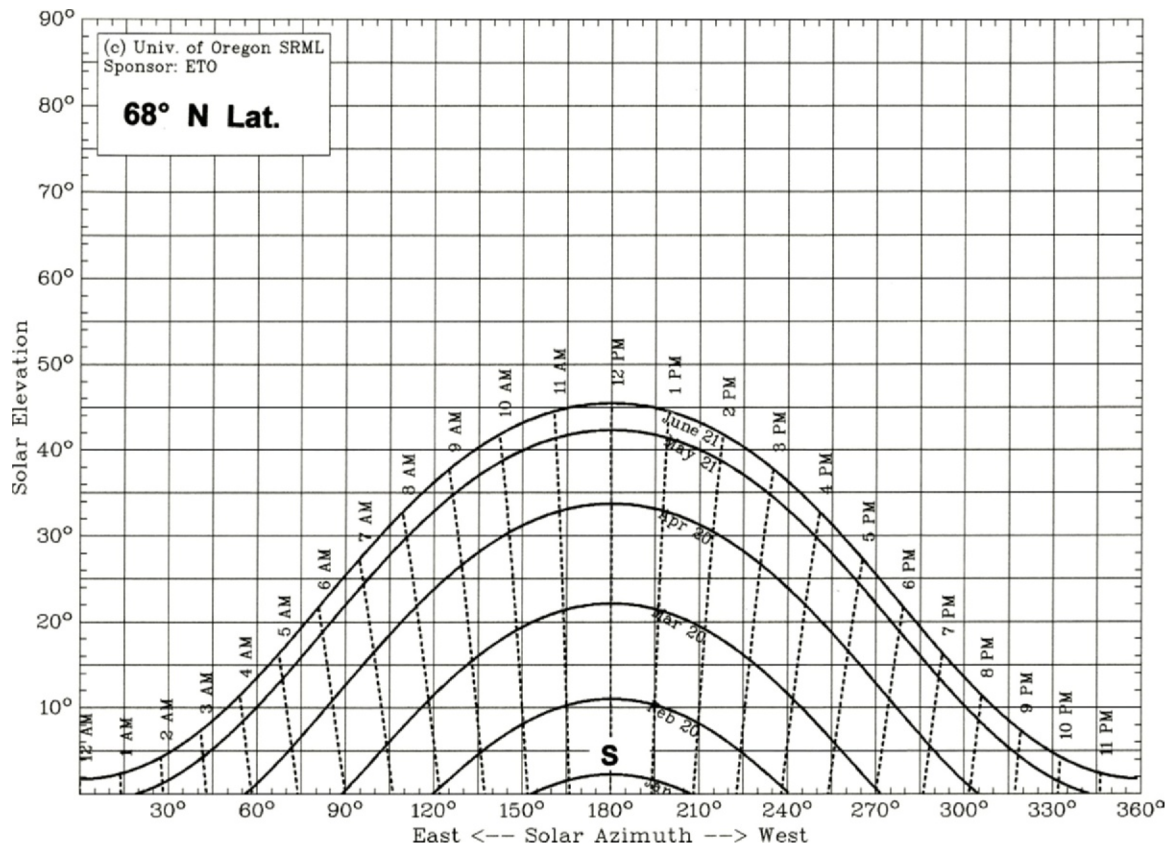

(c) Univ. of Oregon SRML
Sponsor: ETO
48 ° N Lat.
Solar Elevation
Solar Azimuth
East <-- Solar Azimuth --> West
12 PM
11 AM
1 PM
10 AM
2 PM
9 AM
3 PM
8 AM
4 PM
7 AM
5 PM
6 AM
6 PM
5 AM
7 PM
June 21
May 21
Apr 20
Mar 20
Feb 20
Jan 21
Dec 21
S

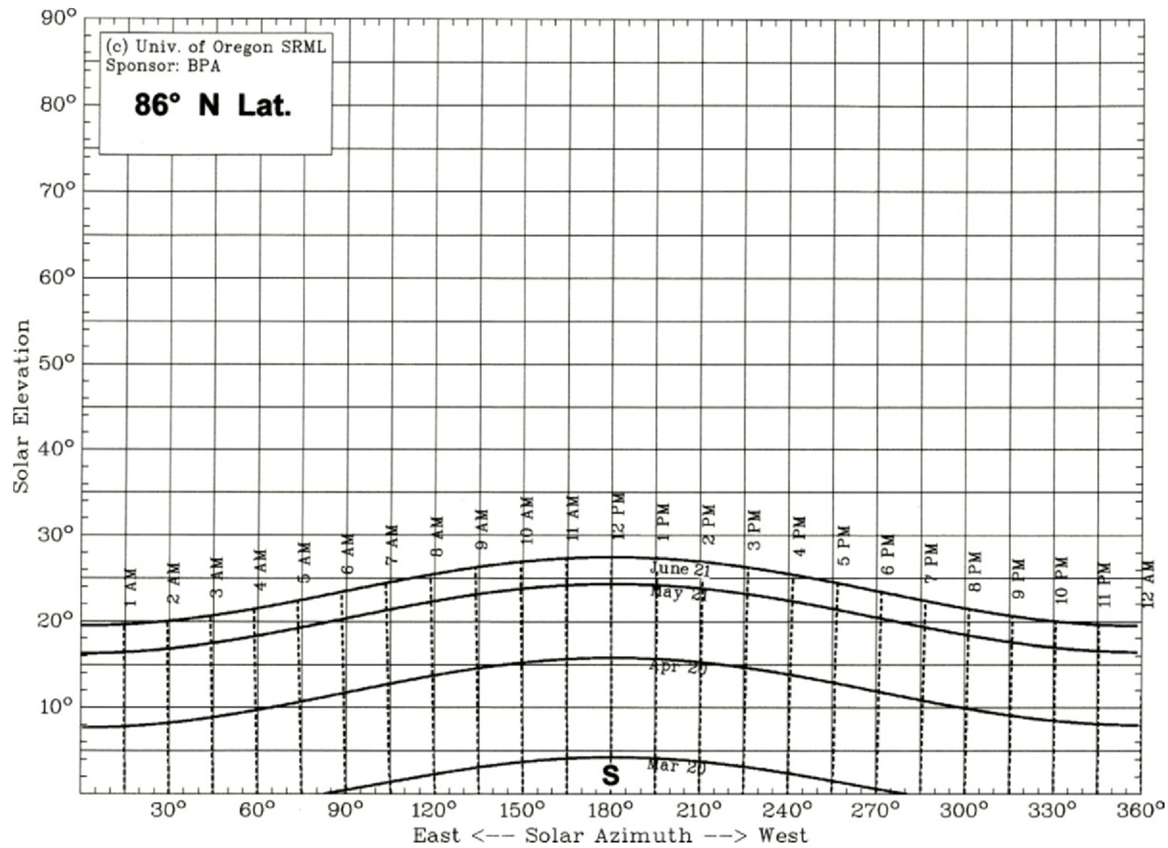

(c) Univ. of Oregon SRML
Sponsor: BPA
52° N Lat.
Solar Elevation
East <-- Solar Azimuth --> West
12 PM
11 AM
1 PM
10 AM
2 PM
9 AM
3 PM
8 AM
4 PM
7 AM
5 PM
6 AM
6 PM
5 AM
7 PM
4 AM
8 PM
June 21
May 21
Apr 20
Mar 20
Feb 20
Jan 21
Dec 21
S

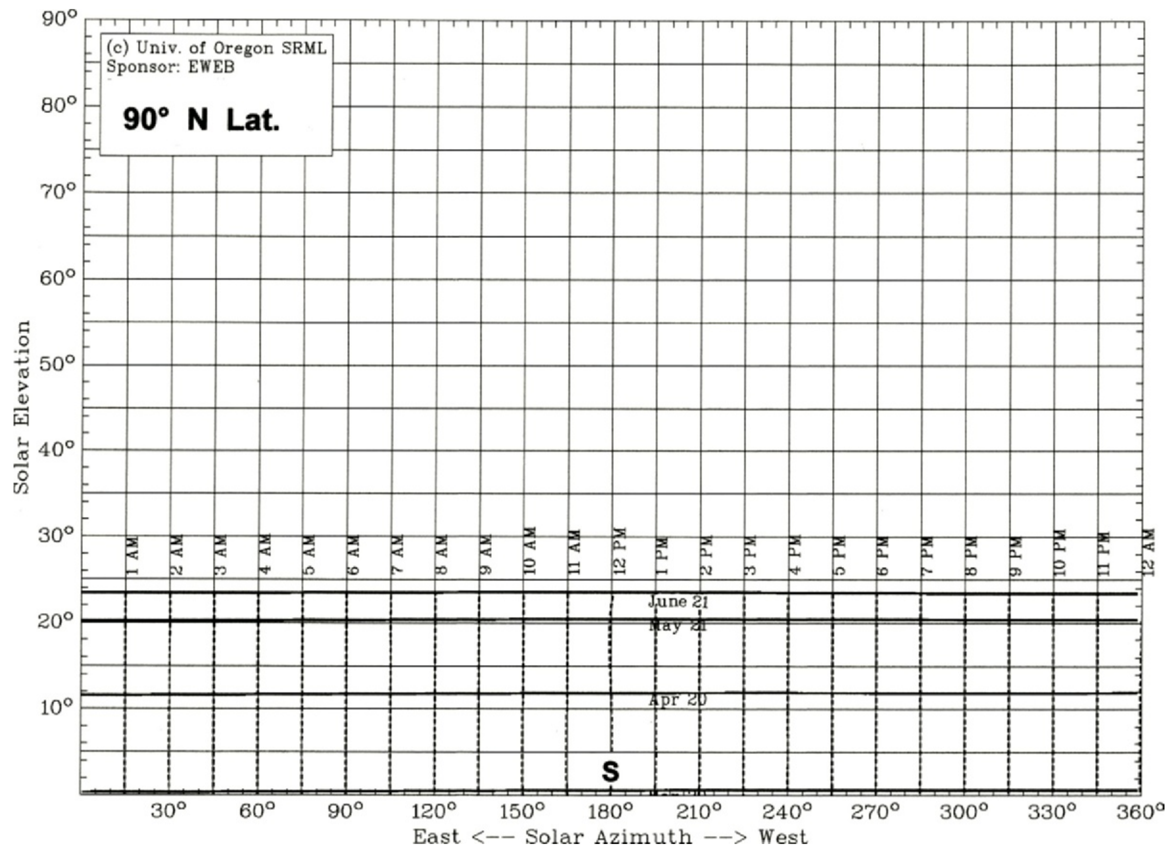

(c) Univ. of Oregon SRML
Sponsor: ETO
56° N Lat.
Solar Elevation
Solar Azimuth
East
West
S
12 PM
1 PM
2 PM
3 PM
4 PM
5 PM
6 PM
7 PM
8 PM
11 AM
10 AM
9 AM
8 AM
7 AM
6 AM
5 AM
4 AM
June 21
May 21
Apr 20
Mar 20
Feb 20
Jan 21
Dec 21


(c) Univ. of Oregon SRML
Sponsor: BPA
60° N Lat.
Solar Elevation
Solar Azimuth
East
West
S
12 PM
1 PM
2 PM
3 PM
4 PM
5 PM
6 PM
7 PM
8 PM
9 PM
11 AM
10 AM
9 AM
8 AM
7 AM
6 AM
5 AM
4 AM
3 AM
June 21
May 21
Apr 20
Mar 20
Feb 20
Jan 21
Dec 21


(c) Univ. of Oregon SRML
Sponsor: BPA
64° N Lat.
Solar Elevation
East <-- Solar Azimuth --> West
2 AM
3 AM
4 AM
5 AM
6 AM
7 AM
8 AM
9 AM
10 AM
11 AM
12 PM
1 PM
2 PM
3 PM
4 PM
5 PM
6 PM
7 PM
8 PM
9 PM
10 PM
June 21
May 21
Apr 20
Mar 20
Feb 20
Jan 21
Dec
S
90°
80°
70°
60°
50°
40°
30°
20°
10°
30°
60°
90°
120°
150°
180°
210°
240°
270°
300°
330°
360°


(c) Univ. of Oregon SRML
Sponsor: ETO
68° N Lat.
Solar Elevation
East <-- Solar Azimuth --> West
12 AM
1 AM
2 AM
3 AM
4 AM
5 AM
6 AM
7 AM
8 AM
9 AM
10 AM
11 AM
12 PM
1 PM
2 PM
3 PM
4 PM
5 PM
6 PM
7 PM
8 PM
9 PM
10 PM
11 PM
June 21
May 21
Apr 20
Mar 20
Feb 20
S
90°
80°
70°
60°
50°
40°
30°
20°
10°
30°
60°
90°
120°
150°
180°
210°
240°
270°
300°
330°
360°


(c) Univ. of Oregon SRML
Sponsor: BPA
86° N Lat.
Solar Elevation
90°
80°
70°
60°
50°
40°
30°
20°
10°
1 AM
2 AM
3 AM
4 AM
5 AM
6 AM
7 AM
8 AM
9 AM
10 AM
11 AM
12 PM
1 PM
2 PM
3 PM
4 PM
5 PM
6 PM
7 PM
8 PM
9 PM
10 PM
11 PM
12 AM
June 21
May 21
Apr 20
Mar 20
S
30°
60°
90°
120°
150°
180°
210°
240°
270°
300°
330°
360°
East <-- Solar Azimuth --> West


(c) Univ. of Oregon SRML
Sponsor: EWEB
90° N Lat.
Solar Elevation
90°
80°
70°
60°
50°
40°
30°
20°
10°
1 AM
2 AM
3 AM
4 AM
5 AM
6 AM
7 AM
8 AM
9 AM
10 AM
11 AM
12 PM
1 PM
2 PM
3 PM
4 PM
5 PM
6 PM
7 PM
8 PM
9 PM
10 PM
11 PM
12 AM
June 21
May 21
Apr 20
S
30°
60°
90°
120°
150°
180°
210°
240°
270°
300°
330°
360°
East <-- Solar Azimuth --> West

APPENDIX C

Solar Altitude and Azimuth Angles

The following table of altitude and azimuth angles were obtained through the use of "Sun Angle," a Web-based calculation tool.

"Sun Angle" can also calculate additional data related to sun angles. It can be found at the Web site of Sustainable by Design, www.susdesign.com/sunangle.

Sustainable by Design is the consulting firm of Christopher Gronbeck, Seattle, Washington. The firm provides solar engineering, green building consulting, graphic design, and Web site design and programming services, primarily within the sustainable energy and architecture fields.

Date	Time	0 Lat		4 Lat		8 Lat		12 Lat		16 Lat		20 Lat	
	(am/pm)	alt	azim	alt	azim	alt	azim	alt	azim	alt	azim	alt	azim
December 21	6/6	0	67										
	7/5	14	66	12	65	10	64	9	64	7	63	5	63
	8/4	27	63	25	62	23	60	21	59	19	57	17	46
	9/3	40	58	38	56	36	53	33	51	31	49	28	48
	10/2	53	49	50	45	46	42	44	40	41	37	38	35
	11/1	62	31	59	27	55	25	52	22	48	21	44	19
	12	67	0	63	0	59	0	55	0	51	0	47	0
Jan/Nov 21	6/6	0	70										
	7/5	14	69	13	68	11	68	10	67	8	66	6	65
	8/4	29	67	27	65	25	64	23	62	21	61	19	59
	9/3	42	63	40	60	38	57	35	55	33	52	30	50
	10/2	54	54	52	50	49	46	46	43	43	40	40	38
	11/1	65	35	62	31	58	28	55	25	51	23	47	21
	12	70	0	66	0	62	0	58	0	54	0	50	0
Feb/Oct 21	6/6	0	79										
	7/5	15	78	14	78	13	76	12	76	11	75	10	74
	8/4	29	77	28	75	27	73	26	71	25	69	23	68
	9/3	44	74	43	71	41	67	40	64	38	61	36	69
	10/2	58	69	57	63	55	58	52	53	50	49	47	46
	11/1	71	53	69	45	66	38	62	33	59	30	56	27
	12	79	0	75	0	71	0	67	0	63	0	59	0
Mar/Sep 21	6/6	0	90	0	90	0	90	0	90	0	90	0	90
	7/5	15	90	15	89	15	88	15	87	14	86	14	85
	8/4	30	90	30	88	30	85	29	83	29	81	28	79
	9/3	45	90	45	86	44	82	44	78	43	75	42	71
	10/2	60	90	60	83	59	76	58	70	56	65	54	59
	11/1	75	90	75	76	73	62	71	52	68	44	65	38
	12	90	0	86	0	82	0	78	0	74	0	70	0
Apr/Aug 21	6/6	0	101	1	101	2	101	2	101	3	101	4	101
	7/5	14	102	15	101	16	99	17	98	17	97	18	96
	8/4	29	103	30	101	31	98	31	96	32	94	32	91
	9/3	43	105	45	102	46	98	46	93	46	90	46	86
	10/2	58	112	59	106	60	99	60	91	60	85	60	78
	11/1	71	128	73	117	75	104	75	89	74	74	73	61
	12	79	180	83	180	87	180	89	0	85	0	81	0
May/Jul 21	6/6	0	110	1	110	3	110	4	110	5	109	7	109
	7/5	15	111	15	110	17	109	18	107	19	106	20	105
	8/4	28	113	30	111	31	109	32	106	33	104	34	101
	9/3	42	117	43	114	45	110	46	107	47	102	48	98
	10/2	54	126	57	121	59	116	60	110	61	103	62	95
	11/1	65	144	68	140	71	131	73	121	75	108	76	93
	12	70	180	74	180	78	180	82	180	86	180	90	180
June 21	6/6	0	113	2	113	3	113	5	113	6	113	8	112
	7/5	14	114	15	113	17	112	18	111	20	110	21	108
	8/4	27	117	29	115	31	113	32	110	33	108	35	105
	9/3	40	122	42	118	44	1115	46	111	47	107	48	103
	10/2	53	131	55	127	57	122	59	116	61	110	62	102
	11/1	62	149	66	145	69	139	71	131	74	120	86	106
	12	67	180	71	180	75	180	79	180	83	180	98	180

Date	Time	24 Lat		28 Lat		32 Lat		36 Lat		40 Lat		44 Lat	
	(am/pm)	alt	azim	alt	azim	alt	azim	alt	azim	alt	azim	alt	azim
December 21	7/5	3	63	1	62								
	8/4	15	55	13	54	10	54	8	53	5	53	3	53
	9/3	35	46	23	45	20	44	17	43	14	42	11	41
	10/2	34	34	31	32	28	31	24	30	21	29	17	29
	11/1	40	18	37	17	33	16	29	16	25	15	21	15
	12	43	0	39	0	35	0	31	0	27	0	23	0
Jan/Nov 21	7/5	5	66	3	65	1	65						
	8/4	17	58	15	57	12	56	10	56	8	55	6	55
	9/3	28	49	25	47	22	46	20	45	17	44	14	43
	10/2	37	36	34	34	31	33	27	32	24	31	20	30
	11/1	44	20	40	18	36	17	32	17	28	16	24	15
	12	46	0	42	0	38	0	34	0	30	0	26	0
Feb/Oct 21	7/5	9	74	8	73	6	72	5	72	4	72	3	72
	8/4	22	66	20	65	18	63	16	62	15	61	13	61
	9/3	34	57	32	54	29	53	27	51	24	49	21	48
	10/2	44	43	41	41	38	39	35	37	32	35	28	34
	11/1	52	24	48	22	45	21	41	20	37	19	33	18
	12	55	0	51	0	47	0	43	0	39	0	35	0
Mar/Sep 21	6/6	0	90	0	90	0	90	0	90	0	90	0	90
	7/5	14	83	13	83	13	82	12	81	11	80	11	79
	8/4	27	77	26	75	25	73	23	71	22	70	21	68
	9/3	40	68	39	65	37	62	35	60	33	57	31	55
	10/2	52	55	50	51	47	47	44	44	42	42	38	48
	11/1	62	33	59	30	55	27	51	24	48	23	44	21
	12	66	0	62	0	58	0	54	0	50	0	46	0
Apr/Aug 21	6/6	5	100	5	100	6	100	7	99	7	99	8	98
	7/5	18	95	18	93	18	92	18	91	19	89	19	88
	8/4	32	89	32	86	31	84	31	81	30	79	29	77
	9/3	45	82	45	78	44	74	43	70	41	67	39	64
	10/2	59	71	57	65	55	60	53	55	51	51	48	48
	11/1	71	51	68	43	65	37	62	33	48	29	55	26
	12	77	0	73	0	69	0	65	0	61	0	57	0
May/Jul 21	5/7							0	115	2	115	4	115
	6/6	8	108	9	108	10	107	12	106	13	106	14	105
	7/5	21	103	22	102	23	100	23	98	24	97	24	95
	8/4	35	99	35	96	35	93	34	90	35	87	35	84
	9/3	48	94	48	89	48	85	48	80	47	76	46	72
	10/2	62	88	62	80	61	73	59	67	57	61	55	56
	11/1	76	77	74	63	72	52	69	44	66	37	63	32
	12	86	0	82	0	78	0	74	0	70	0	66	0
June 21	5/7					0	118	2	117	4	117	6	117
	6/6	9	112	11	111	12	110	13	107	15	108	16	107
	7/5	22	107	23	105	24	103	25	102	26	100	27	98
	8/4	35	102	36	100	37	97	37	94	37	91	37	88
	9/3	49	99	49	94	50	89	49	85	49	80	48	76
	10/2	63	95	63	87	62	80	61	72	60	66	58	60
	11/1	76	91	76	74	74	61	72	50	69	42	66	36
	12	89	0	85	0	81	0	77	0	73	0	69	0

	Time	48 Lat		52 Lat		56 Lat		60 Lat		64 Lat		68 Lat	
Date	(am/pm)	alt	azim	alt	azim	alt	azim	alt	azim	alt	azim	alt	azim
December 21	8/4	1	53										
	9/3	8	41	5	41	2	40						
	10/2	14	28	10	28	7	27	3	27				
	11/1	17	14	13	14	10	14	6	14	2	14		
	12	19	0	15	0	11	0	7	0	3	0		
Jan/Nov 21	8/4	3	55	1	54								
	9/3	11	43	8	42	5	42	2	42				
	10/2	17	29	13	29	10	28	6	28	3	28		
	11/1	21	15	17	15	13	14	9	14	5	14	1	14
	12	22	0	18	0	14	0	10	0	6	0	2	0
Feb/Oct 21	7/5	1	71	0	71								
	8/4	11	60	9	59	7	59	4	58	2	58	0	58
	9/3	19	47	16	46	13	45	10	45	7	44	5	44
	10/2	25	33	22	32	18	31	15	30	11	30	8	30
	11/1	29	17	26	16	22	16	18	15	14	15	10	15
	12	31	0	27	0	23	0	19	0	15	0	11	0
	6/6	0	90	0	90	0	90	0	90	0	90	0	90
Mar/Sep 21	7/5	10	7 9	9	78	8	77	7	77	6	76	6	76
	8/4	20	67	18	65	16	64	14	63	13	63	11	62
	9/3	29	53	26	52	23	50	21	49	18	48	15	47
	10/2	35	38	32	36	29	35	26	34	22	33	19	32
	11/1	40	20	37	19	33	18	29	17	25	16	21	16
	12	42	0	38	0	34	0	30	0	26	0	22	0
Apr/Aug 21	5/7					1	109	2	108	4	108	5	108
	6/6	8	98	9	97	9	96	10	96	10	95	10	94
	7/5	18	86	18	85	18	84	17	83	17	81	16	80
	8/4	28	75	27	73	26	71	24	69	23	67	21	66
	9/3	38	61	36	58	33	56	31	54	29	52	26	51
	10/2	46	44	43	42	39	39	36	38	33	36	30	34
	11/1	51	24	48	22	44	21	40	19	36	18	32	17
	12	53	0	49	0	45	0	41	0	37	0	33	0
May/Jul 21	2/10											1	152
	3/9									1	138	4	138
	4/8					1	125	3	125	6	125	8	125
	5/7	5	114	7	114	8	113	10	113	12	112	13	111
	6/6	15	104	16	193	16	101	17	100	18	99	18	98
	7/5	25	93	25	91	25	89	25	87	24	86	24	84
	8/4	35	82	34	79	33	76	32	74	31	71	30	69
	9/3	44	68	43	65	41	61	39	59	37	56	35	54
	10/2	53	52	50	48	48	44	45	41	42	39	38	37
	11/1	60	29	56	26	52	23	49	22	45	20	41	19
	12	62	0	58	0	54	0	50	0	46	0	42	0
June 21	12 mid											1	180
	1/11											2	166
	2/10									0	153	4	153
	3/9							1	139	4	139	7	139
	4/8			2	127	4	127	7	127	9	126	11	126
	5/7	8	116	10	116	11	115	13	114	15	114	16	113
	6/6	17	106	18	105	19	104	20	102	21	101	22	99
	7/5	27	96	27	94	27	92	28	90	27	87	27	85
	8/4	37	85	37	82	36	79	35	76	34	73	33	71
	9/3	47	72	45	68	44	64	42	61	40	58	38	55
	10/2	56	55	53	50	51	46	48	43	45	40	42	38
	11/1	63	31	59	28	56	25	52	23	48	21	44	19
	12	65	0	61	0	57	0	53	0	49	0	45	0

	Time	72 Lat		76 Lat		82 Lat		86 Lat		90 Lat	
Date	(am/pm)	alt	azim	alt	azim	alt	azim	alt	azim	alt	azim
December 21											
Jan/Nov 21											
Feb/Oct 21	9/3	2	44								
	10/2	5	29	0	29						
	11/1	6	15	1	15						
	12	7	0	2	0						
Mar/Sep 21	12 mid									0	180
	1/11									0	165
	2/10									0	150
	3/9									0	135
	4/8									0	120
	5/7									0	105
	6/6	0	90	0	90	0	90	0	90	0	90
	7/5	5	76	3	75	2	75	1	75	0	75
	8/4	9	61	6	61	4	60	2	60	0	60
	9/3	13	46	9	46	6	45	3	45	0	45
	10/2	16	31	11	31	6	30	3	30	0	30
	11/1	17	16	13	15	8	15	4	15	0	15
	12	18	0	13	0	8	0	4	0	0	0
Apr/Aug 21	12 mid					3	180	7	180	11	180
	1/11					3	165	7	165	11	165
	10/2					4	150	8	150	11	150
	3/9			2	136	6	136	8	135	11	135
	4/8	2	122	5	122	7	121	9	121	11	120
	5/7	6	108	8	107	9	106	10	106	11	105
	6/6	11	93	11	93	11	92	11	91	11	90
	7/5	15	79	14	78	13	77	12	76	11	75
	8/4	20	64	18	63	15	62	13	61	11	60
	9/3	24	49	20	48	17	46	14	46	11	45
	10/2	27	33	22	32	18	31	15	30	11	30
	11/1	29	17	24	16	19	16	15	15	11	15
	12	29	0	24	0	19	0	15	0	11	0
May / Jul 21	12 mid	2	180	7	180	12	180	16	180	20	180
	1/11	3	166	7	166	12	166	16	165	20	165
	2/10	4	152	9	152	13	151	16	151	20	150
	3/9	7	138	11	137	14	137	17	136	20	135
	4/8	10	124	13	123	16	122	18	121	20	120
	5/7	14	110	16	109	18	108	19	106	20	105
	6/6	19	96	19	95	20	93	20	91	20	90
	7/5	24	82	23	80	22	78	21	76	20	75
	8/4	28	67	26	65	24	63	22	61	20	60
	9/3	32	52	29	49	26	47	23	46	20	45
	10/2	35	35	31	33	27	32	23	31	20	30
	11/1	37	18	33	17	28	16	24	15	20	15
	12	38	0	33	0	28	0	24	0	20	0
June 21	12 mid	5	180	10	180	15	180	19	180	23.43	180
	1/11	6	166	11	166	16	166	20	165	23.43	165
	2/10	8	152	12	152	16	151	20	151	23.43	150
	3/9	10	139	14	138	18	137	21	136	23.43	135
	4/8	14	125	16	124	19	123	21	121	23.43	120
	5/7	18	111	19	110	21	108	22	107	23.43	105
	6/6	22	98	23	96	23	93	23	92	23.43	90
	7/5	27	83	26	81	25	78	24	77	23.43	75
	8/4	31	68	29	66	27	63	25	62	23.43	60
	9/3	35	53	32	50	29	48	26	46	23.43	45
	10/2	39	36	34	34	30	32	27	31	23.43	30
	11/1	41	18	36	17	31	16	27	15	23.43	15
	12	41	0	36	0	31	0	27	0	23.43	0

APPENDIX D

Methods for Estimating the Height of Trees, Buildings, etc.

To determine solar access and shading, one needs to know the approximate height of objects around the site being investigated. This is the case whether model studies, graphical analyses, or computer analyses are used. Four methods are described below for finding the height of a tree; of course, these methods work equally well for buildings or other objects.

D.1 PROPORTIONAL-SHADOW METHOD

This method can be used only on sunny days during the hours when shadows are fairly long.

Set up a vertical stick so that you can measure its shadow at the same time the shadow of the tree is visible (Fig. D.1). Measure both shadows and the height of the stick. You can then determine the height of the tree by means of the following equation:

$$\frac{H}{S} = \frac{h}{s}$$

or

$$H = S \times \frac{h}{s}$$

D.2 SIMILAR-TRIANGLE METHOD

Although this method can be used whether the sun is shining or not, it is important to avoid looking directly into the sun on clear days. Hold a square with one leg horizontal and the other vertical. Use a small level on the horizontal leg or hang a weighted string from the top of the vertical arm to level the square. Sight along the square, and place a finger where the sight line intersects the vertical arm to find the height (h), as seen in Fig. D.2.

Then, by similar triangles:

$$\frac{H}{D} = \frac{h}{d}$$

or

$$H = D \times \frac{h}{d}$$

and the height of the object = $H + P$.

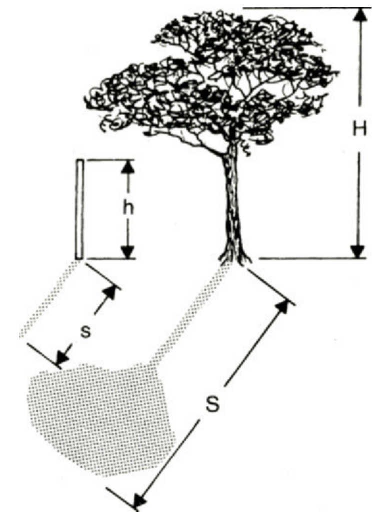


Figure D.1 The proportional-shadow method of finding the height of an object.

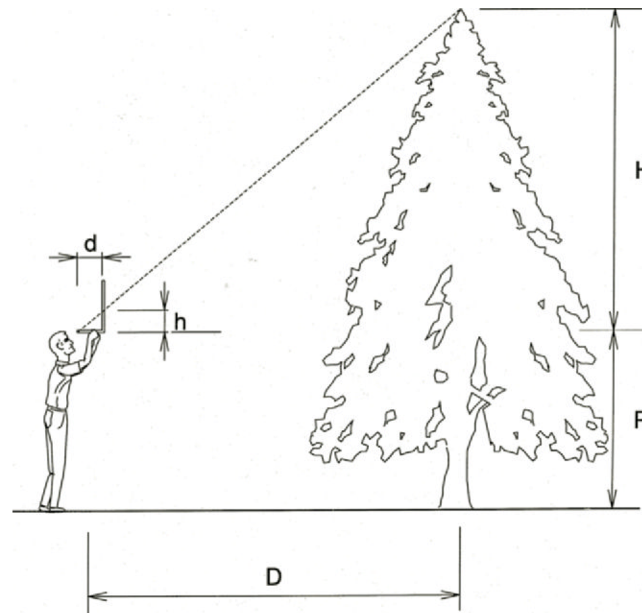


Figure D.2 The similar-triangle method of finding the height of an object.

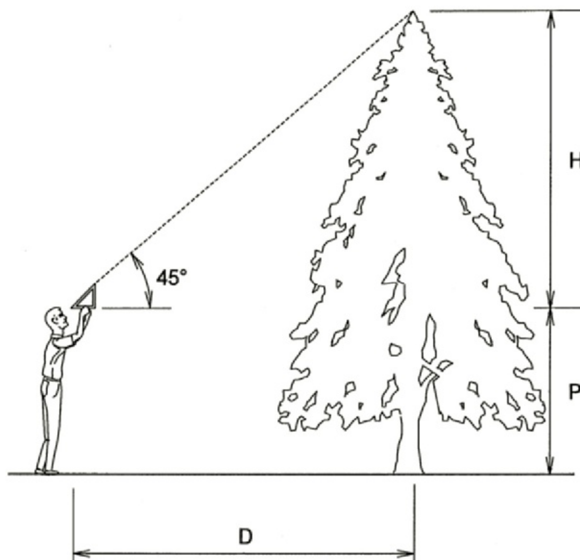


Figure D.3 The 45° right-triangle method of finding the height of an object.

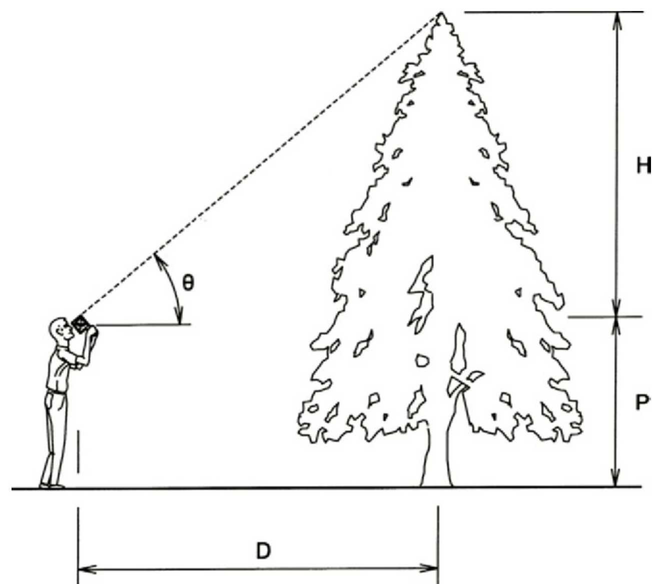


Figure D.4 The trigonometric method of finding the height of an object.

D.3 45° RIGHT-TRIANGLE METHOD

This method is a special case of the similar-triangle method. If the site allows one to sight along the hypotenuse of a 45° right triangle, the unknown height of the object above the triangle will simply be the horizontal distance to the sighting point (Fig. D.3).

$$H = D$$

and the height of the object $= H + P$.

D.4 TRIGONOMETRIC METHOD

Use a transit or other device to measure the vertical angle θ (Fig. D.4). Commercially available devices and a simple, inexpensive, do-it-yourself device to measure this angle are described in Section D.5.

Use the following equation to find (H):

$$H = D \tan \theta$$

and the height of the object $= H + P$.

D.5 TOOLS FOR MEASURING VERTICAL ANGLES

Of course, a professional transit can be used, but that tool is usually too expensive for this purpose. However, a much less expensive tool can still give precise results. A **clinometer** is a small pocket tool used for finding vertical angles, and it costs about $200 (Fig. D.5a). It is widely used by foresters for finding the height of trees.*

Also available for about $15 is a special construction protractor, which is meant for finding the slope

*Clinometers can be obtained from Forestry Suppliers, Inc., P.O. Box 8397, Jackson, MS 39284-8397, tel. 1-800-647-5368, www.forestry-suppliers.com



Figure D.5a This construction protractor was purchased for about $15.



Figure D.5b A commercially available clinometer is used for finding vertical angles.

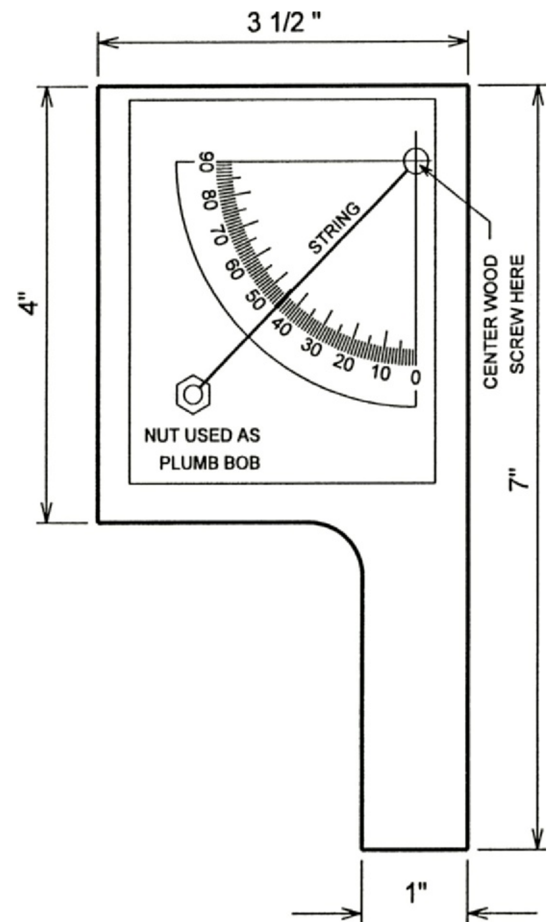


Figure D.5c Construction drawing for building the angle-finder. Any similar dimensions will work equally well.



Figure D.5d Here, the angle-finder is being used to determine the height of an object.

of pipes or structural members (Fig. D.5b). This tool is used much like the angle-finder described below.

The angle-finder is a simple and inexpensive do-it-yourself tool for measuring vertical angles, which can be cut from a 1 × 4 board about 7 in. (2 × 10 × 17 cm) long (Fig. D.5c). The 90° scale can be photocopied from Fig. I.4f in Appendix I. Hang a plumb line from a screw inserted at the point shown in Figure D.5d. A small machine nut can make a handy plumb bob.

To measure the altitude angle to the top of some object, hold the angle-finder in the vertical plane and sight along its top edge. After the plumb line has stopped swaying, place a finger on the line and measure the angle (Fig. D.5d).

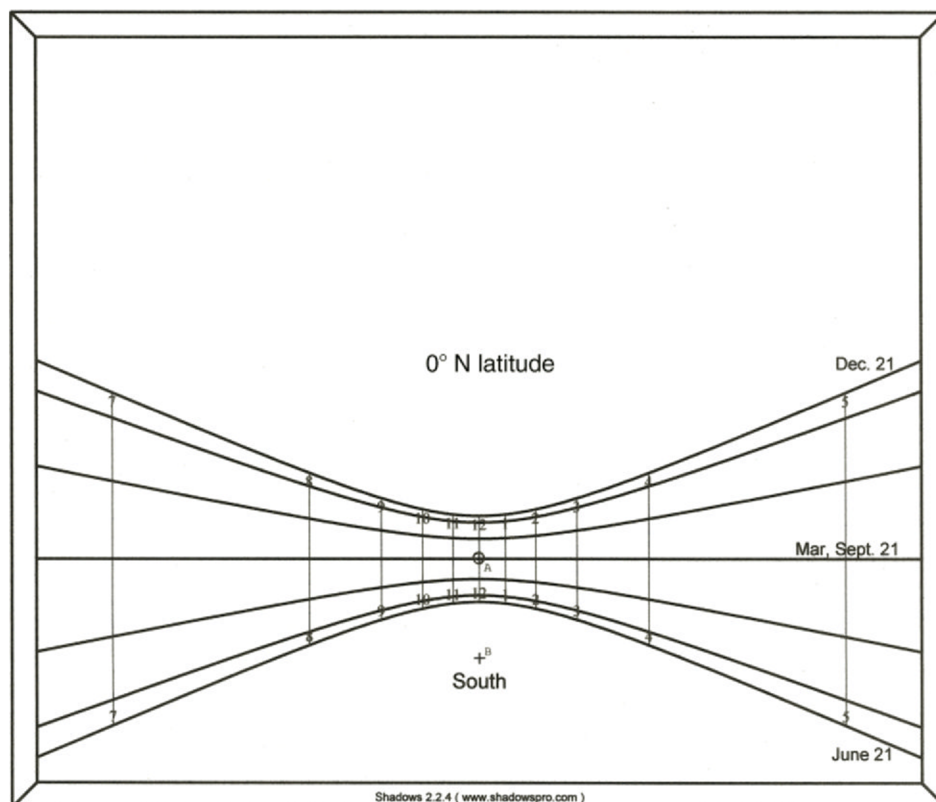
APPENDIX E

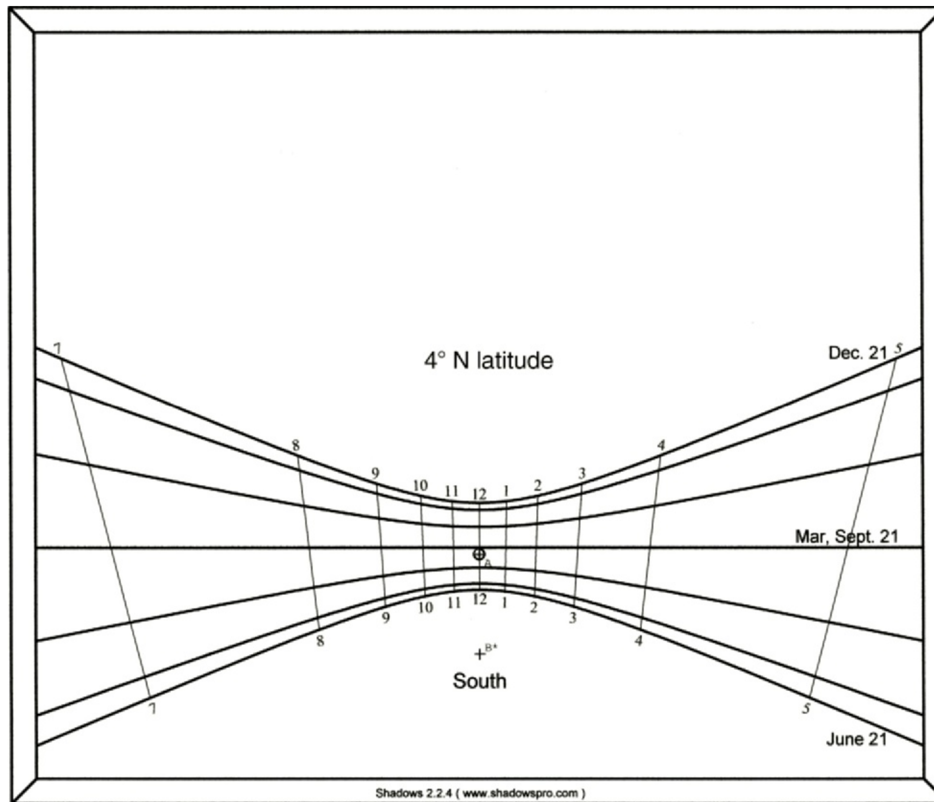
Sundials

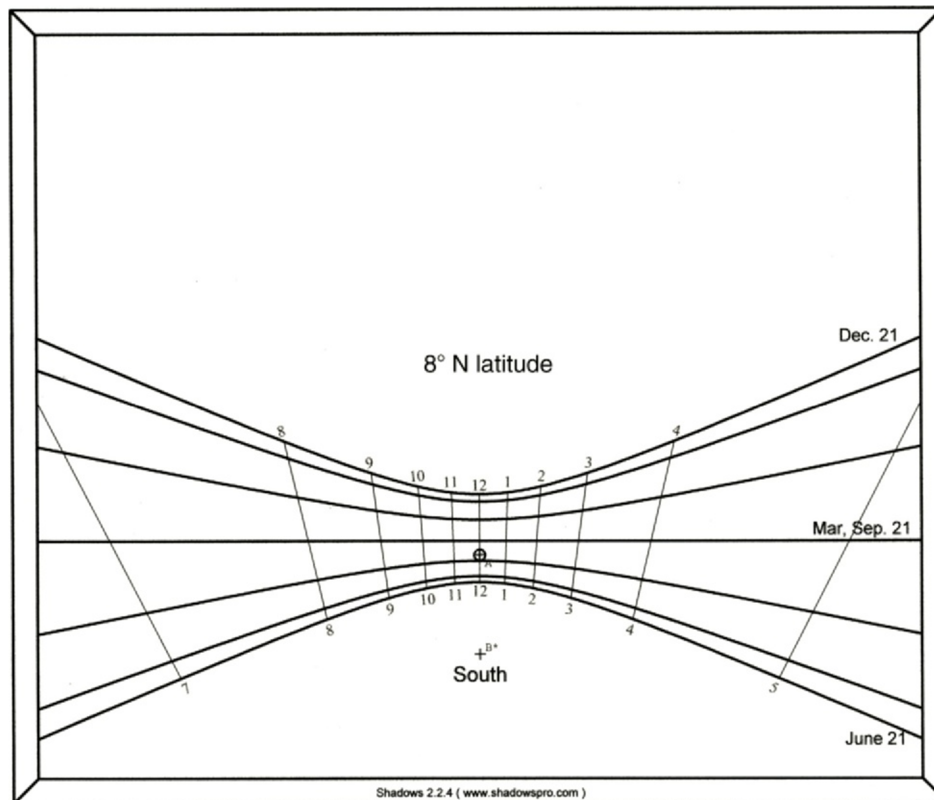
Sundials, also known as sun peg charts, can be used in conjunction with a heliodon to simulate sun angles. This application of sundials is explained in Appendix I, Section 6.18, and Section 13.19.

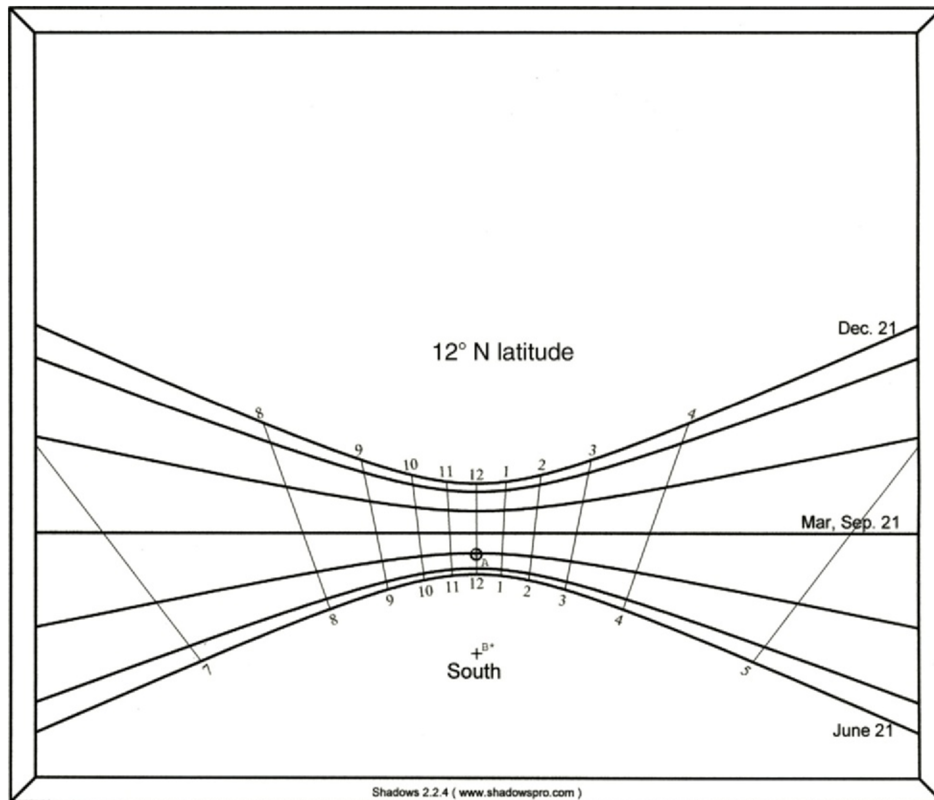
Each sundial requires a peg (gnomon) of a particular height to cast the proper shadow. The length of the gnomon is indicated on each sundial so that enlargements or reductions of the sundials are convenient to make. Copy the sundial that comes closest to the latitude required and glue it on a piece of wood. Hammer a nail vertically into the wood at point A so that it projects a distance AB above the wood.

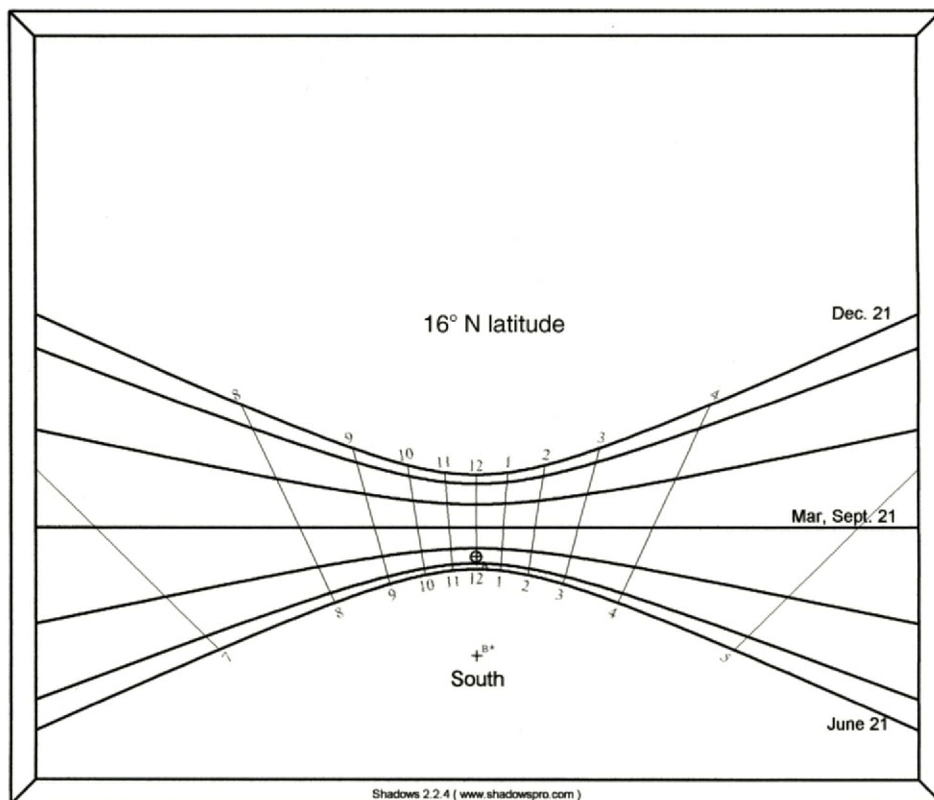
These charts were created from a freeware program called "Shadows" downloaded from the Web site www.shadowspro.com. The software was created by Francois Blateyron (copyright 1997–2006), who also makes available more sophisticated software for designing sundials. The above Web site can be used to create a sundial for any latitude on earth.

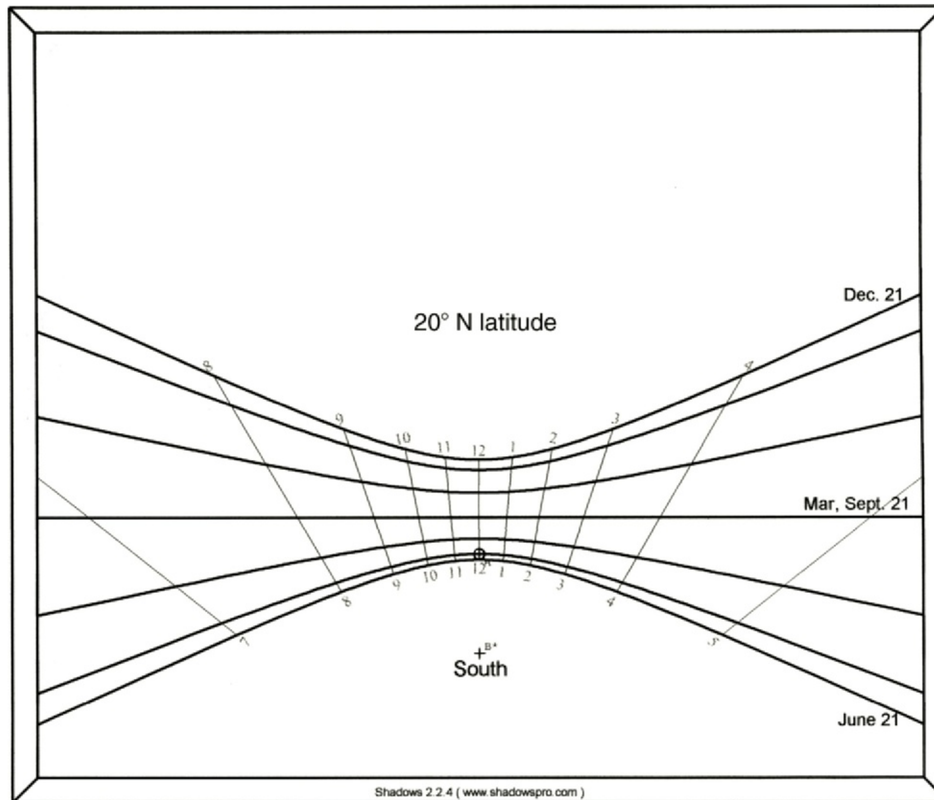


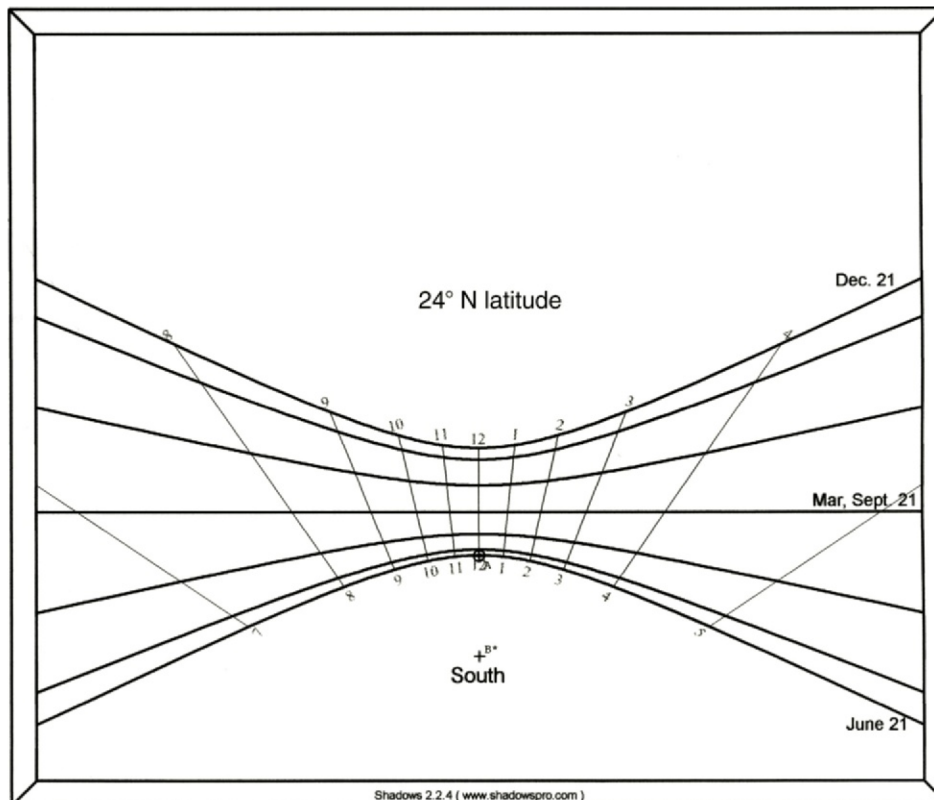

4° N latitude
Dec. 21
Mar, Sept. 21
June 21
South
7
8
9
10
11
12
1
2
3
4
5
Shadows 2.2.4 (www.shadowspro.com)

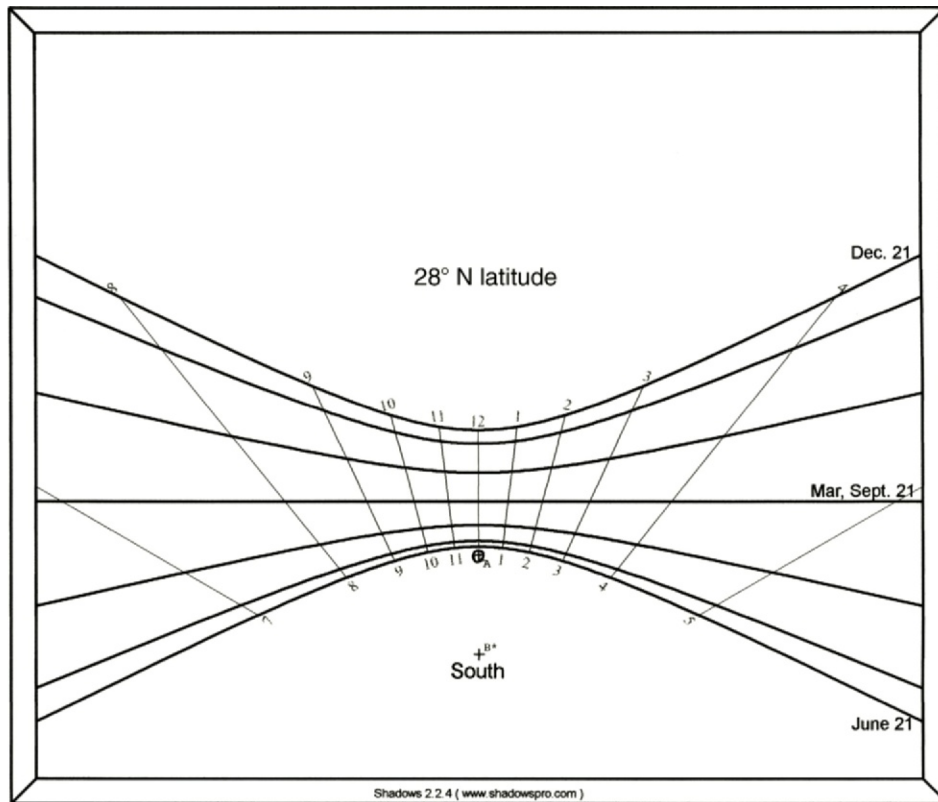

8° N latitude
Dec. 21
Mar, Sep. 21
June 21
South
7
8
9
10
11
12
1
2
3
4
5
Shadows 2.2.4 (www.shadowspro.com)

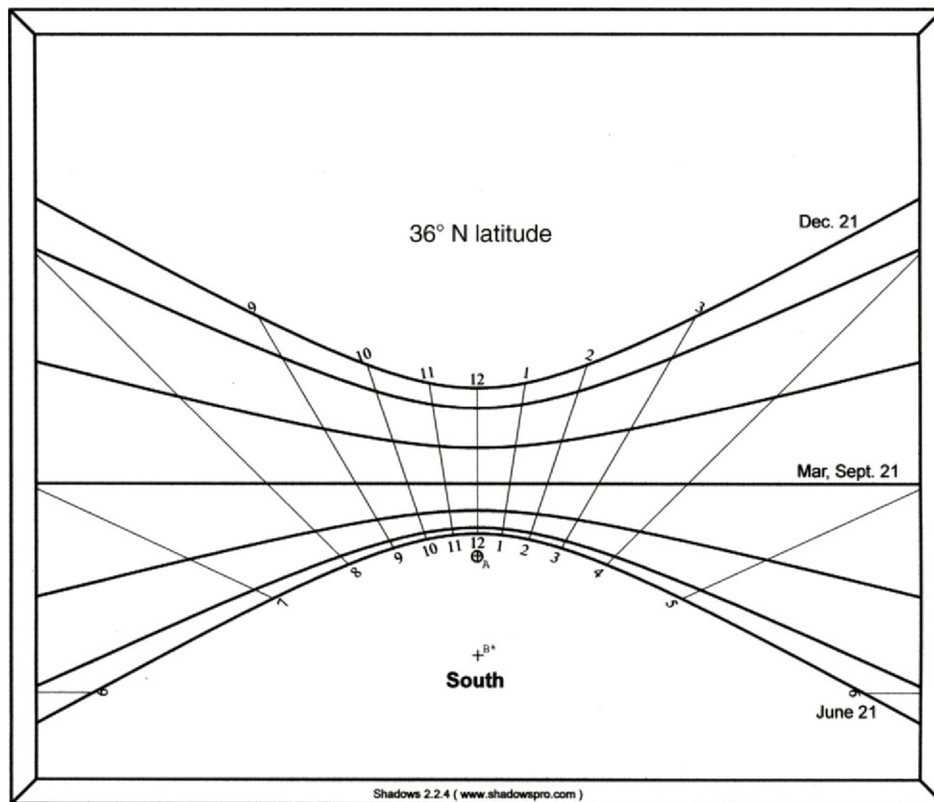

12° N latitude
Dec. 21
Mar, Sep. 21
June 21
South
8
9
10
11
12
1
2
3
4
7
5
Shadows 2.2.4 (www.shadowspro.com)

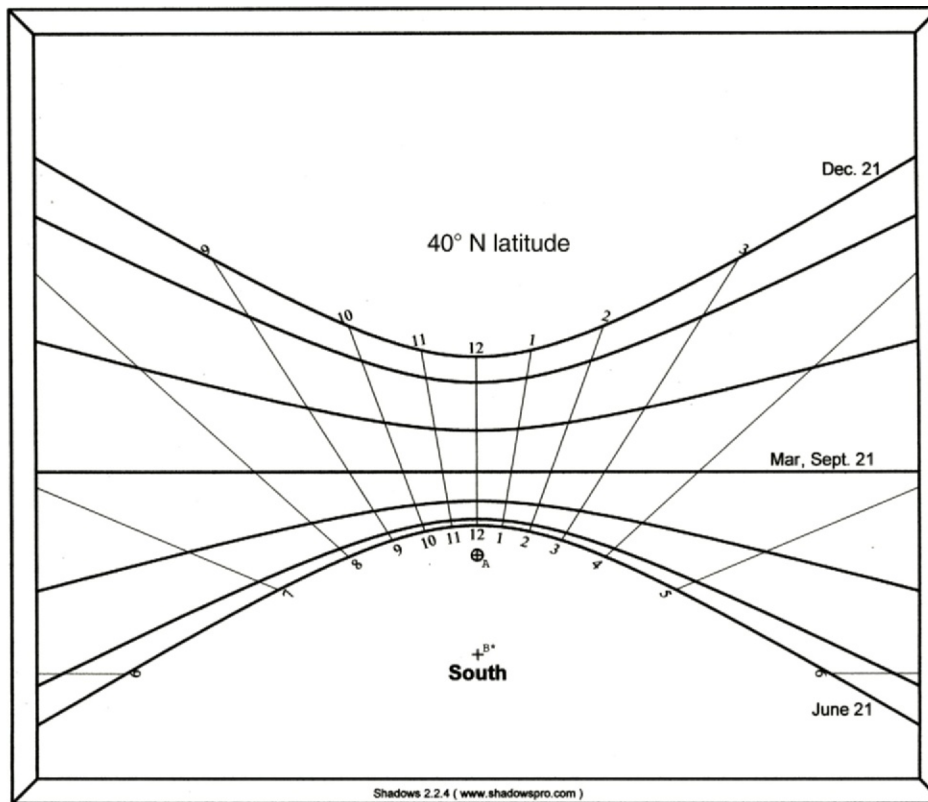

16° N latitude
Dec. 21
Mar, Sept. 21
June 21
South
8
9
10
11
12
1
2
3
4
7
5
Shadows 2.2.4 (www.shadowspro.com)

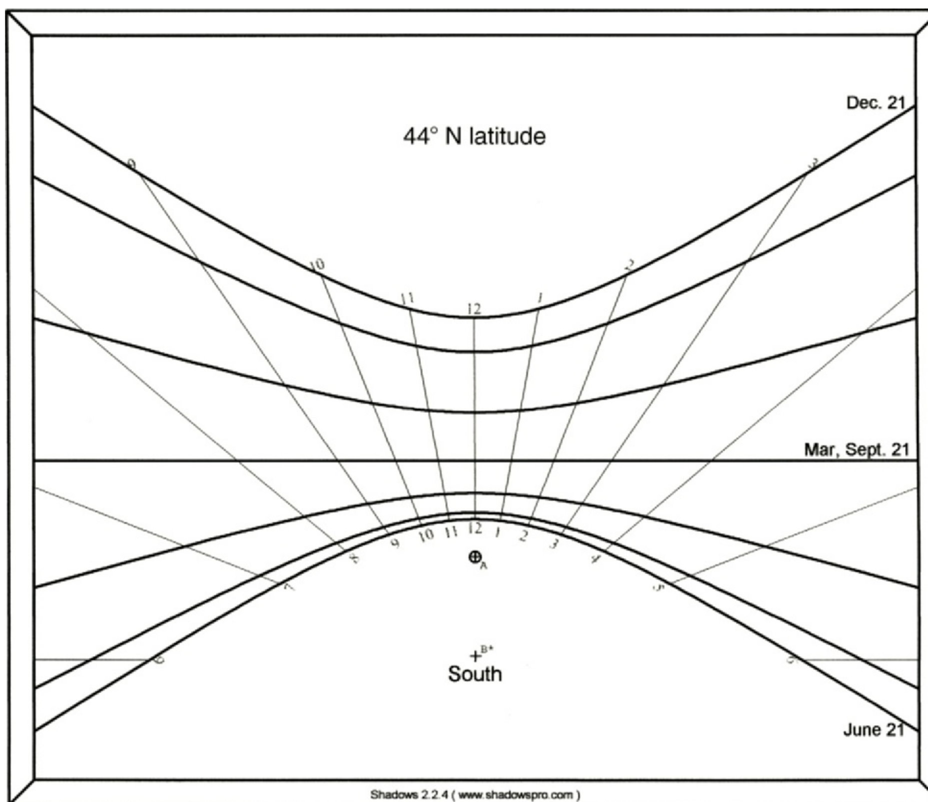

20° N latitude
Dec. 21
Mar, Sept. 21
June 21
South
Shadows 2.2.4 (www.shadowspro.com)

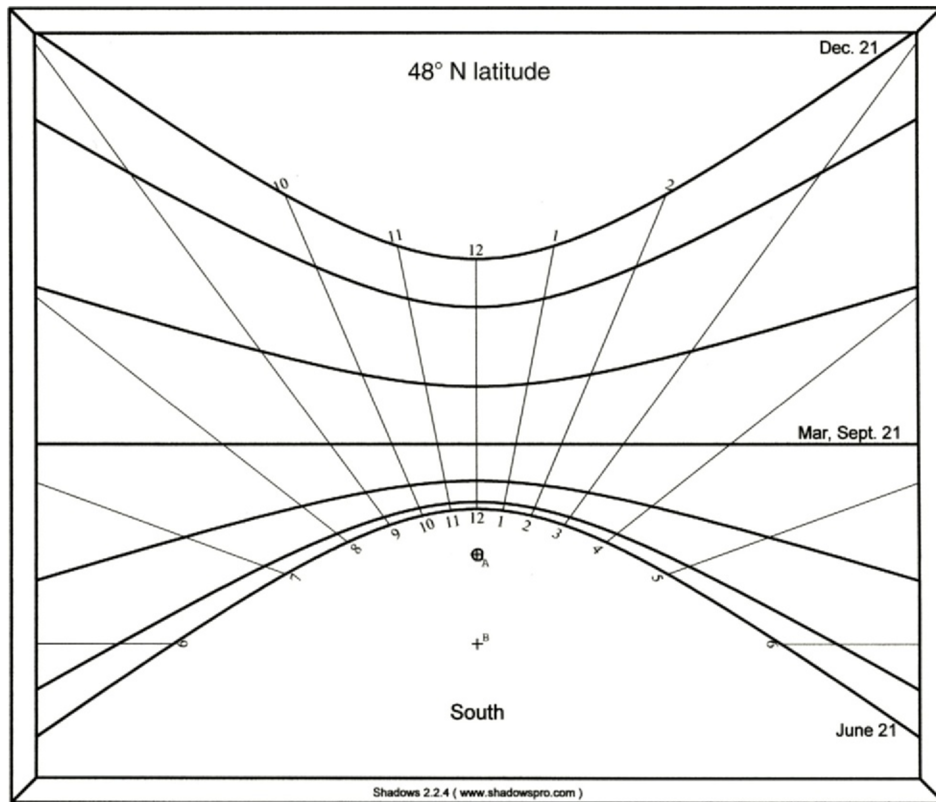

24° N latitude
Dec. 21
Mar, Sept. 21
June 21
South
Shadows 2.2.4 (www.shadowspro.com)

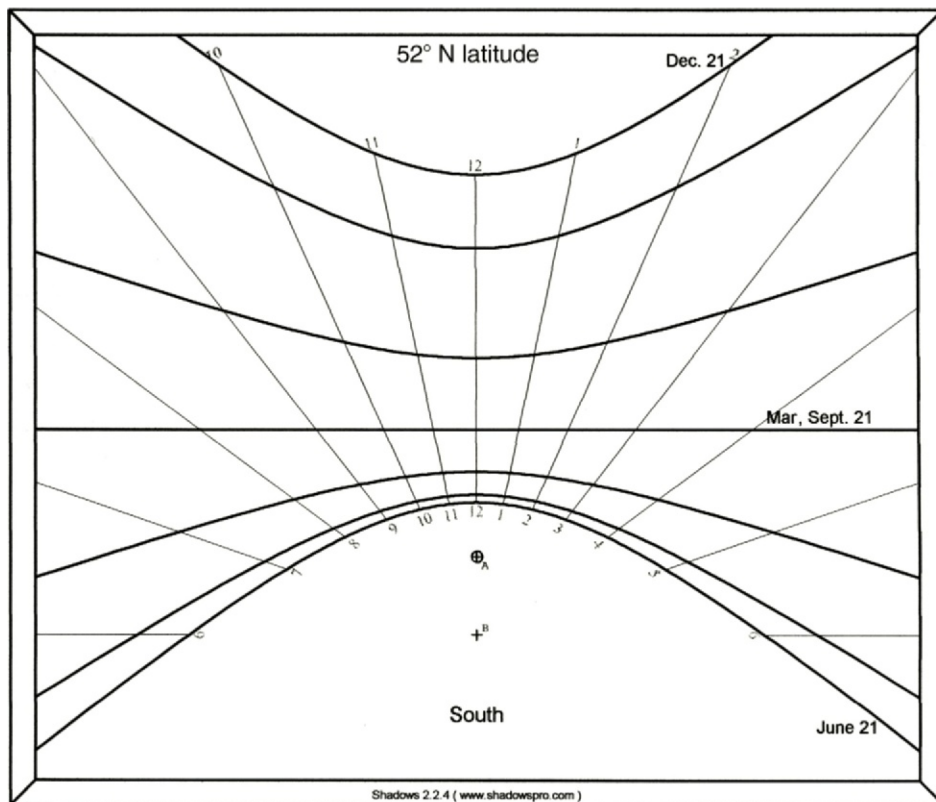

28° N latitude
Dec. 21
Mar, Sept. 21
June 21
South
Shadows 2.2.4 (www.shadowspro.com)

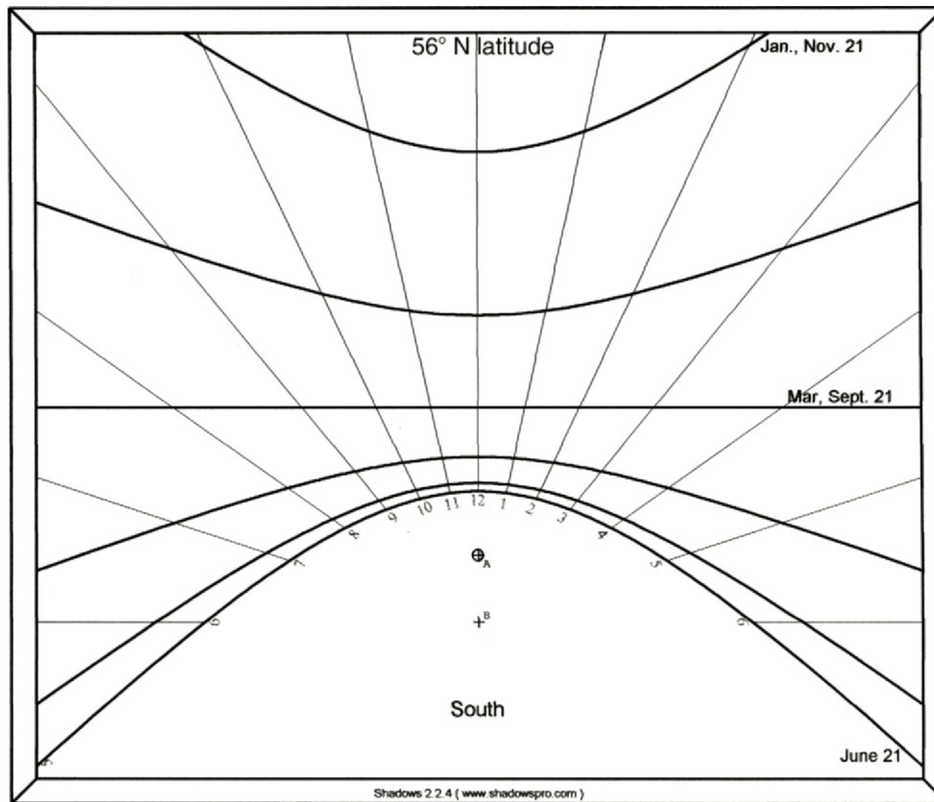

36° N latitude
Dec. 21
Mar, Sept. 21
June 21
South
Shadows 2.2.4 (www.shadowspro.com)

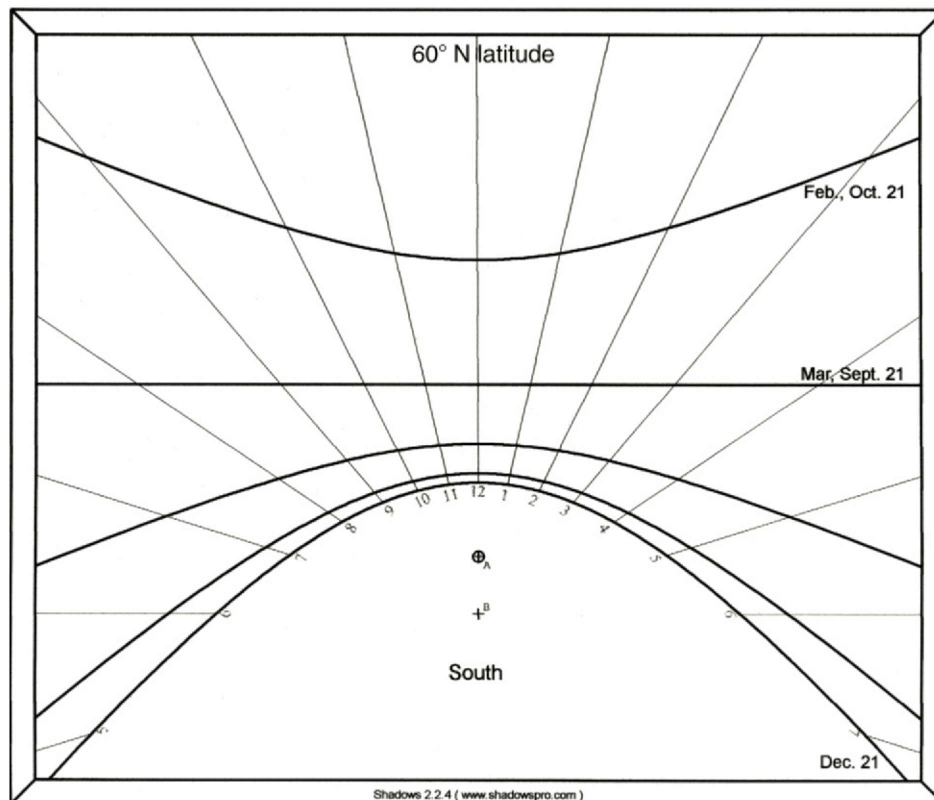

Dec. 21
40° N latitude
Mar, Sept. 21
South
June 21
Shadows 2.2.4 (www.shadowspro.com)

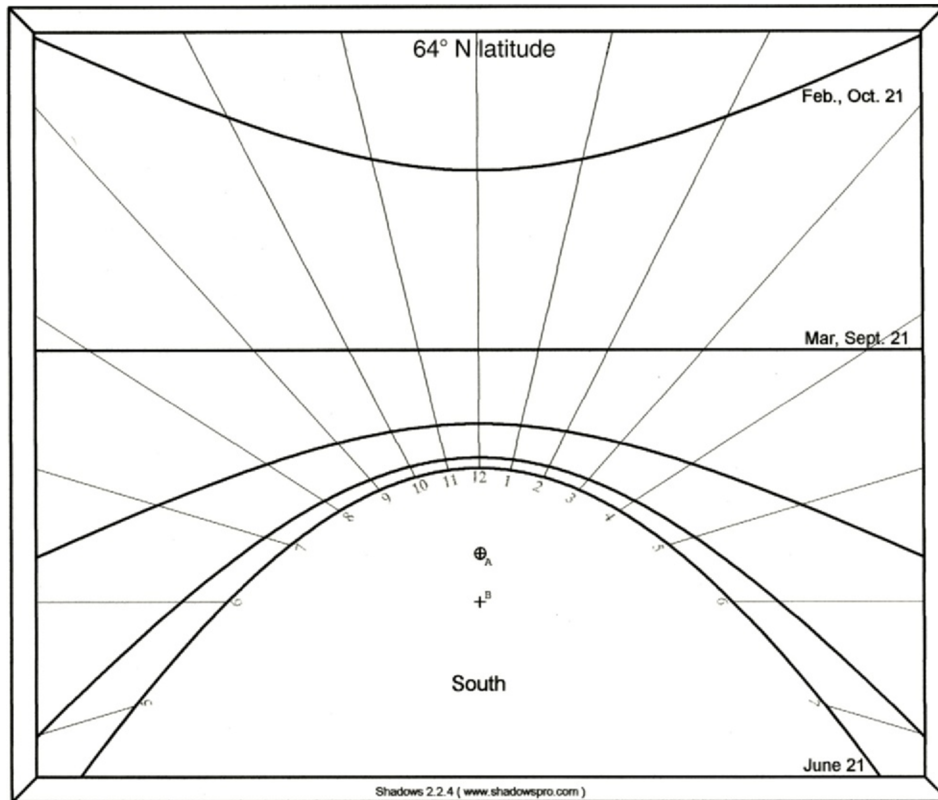

Dec. 21
44° N latitude
Mar, Sept. 21
South
June 21
Shadows 2.2.4 (www.shadowspro.com)

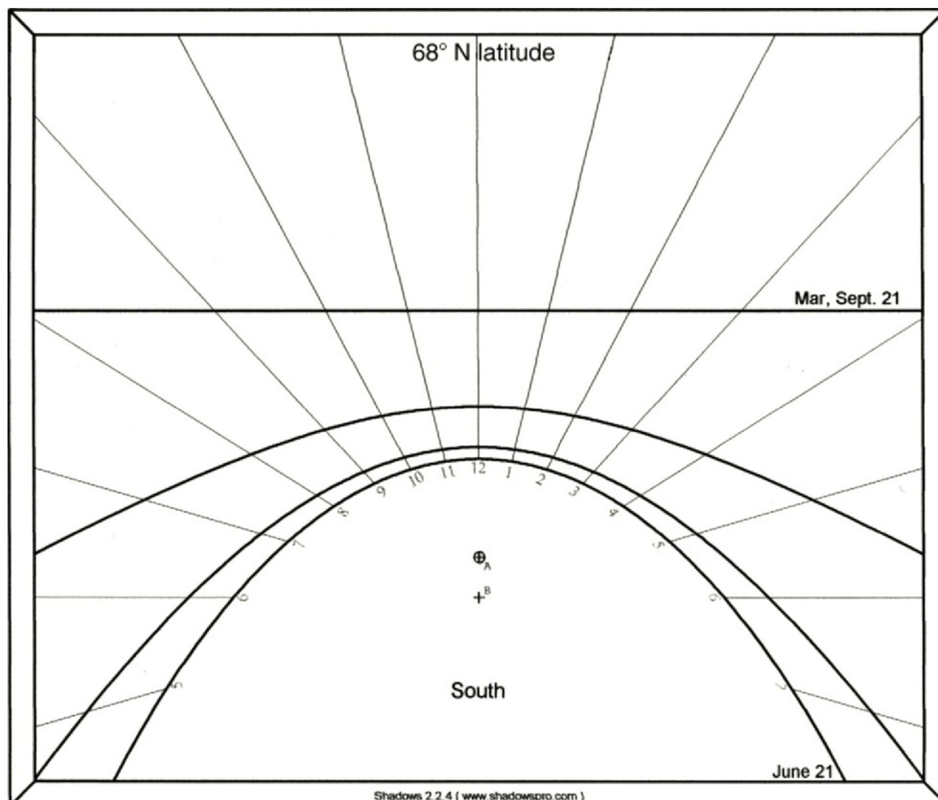

48° N latitude
Dec. 21
Mar, Sept. 21
South
June 21
Shadows 2.2.4 (www.shadowspro.com)

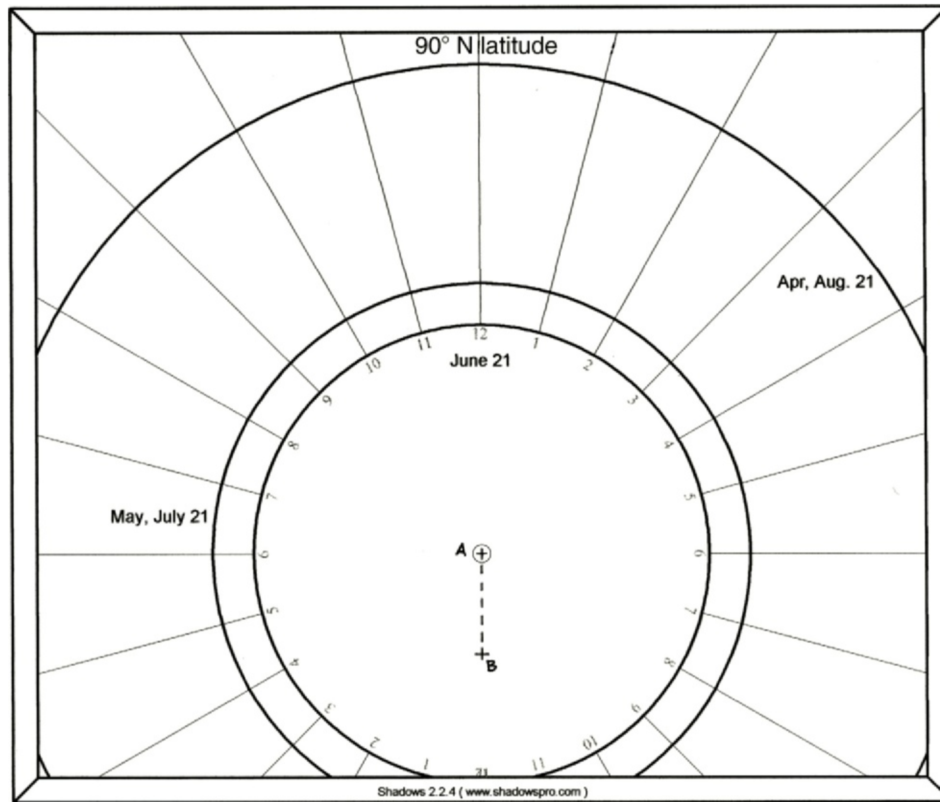

52° N latitude
Dec. 21
Mar, Sept. 21
South
June 21
Shadows 2.2.4 (www.shadowspro.com)


56° N latitude
Jan., Nov. 21
Mar, Sept. 21
12
1
2
3
4
5
6
7
8
9
10
11
South
June 21
Shadows 2.2.4 (www.shadowspro.com)


60° N latitude
Feb., Oct. 21
Mar, Sept. 21
12
1
2
3
4
5
6
7
8
9
10
11
South
Dec. 21
Shadows 2.2.4 (www.shadowspro.com)


64° N latitude
Feb., Oct. 21
Mar, Sept. 21
10 11 12 1 2 3 4 5 6 7 8 9
South
June 21
Shadows 2.2.4 (www.shadowspro.com)


68° N latitude
Mar, Sept. 21
10 11 12 1 2 3 4 5 6 7 8 9
South
June 21
Shadows 2.2.4 (www.shadowspro.com)


90° N latitude
Apr, Aug. 21
June 21
May, July 21
A
B
Shadows 2.2.4 (www.shadowspro.com)

APPENDIX F

Sun-Path Models

F.1 INTRODUCTION

Sun-path models can be very useful in visualizing the complex motion of the sun. The following diagrams make it quite easy to construct a sun-path model for latitudes at 4° intervals. These diagrams are orthographic projections of a sky dome. Normal sun-path diagrams, as found in Appendix A, are not appropriate for this purpose. See Section 6.14 for an additional discussion of these sun-path models.

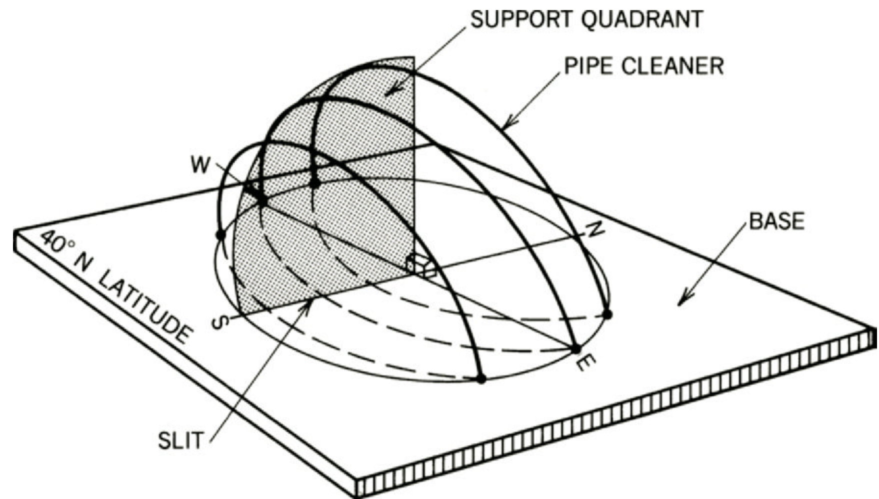


Figure F.2a The parts of a sun-path model.

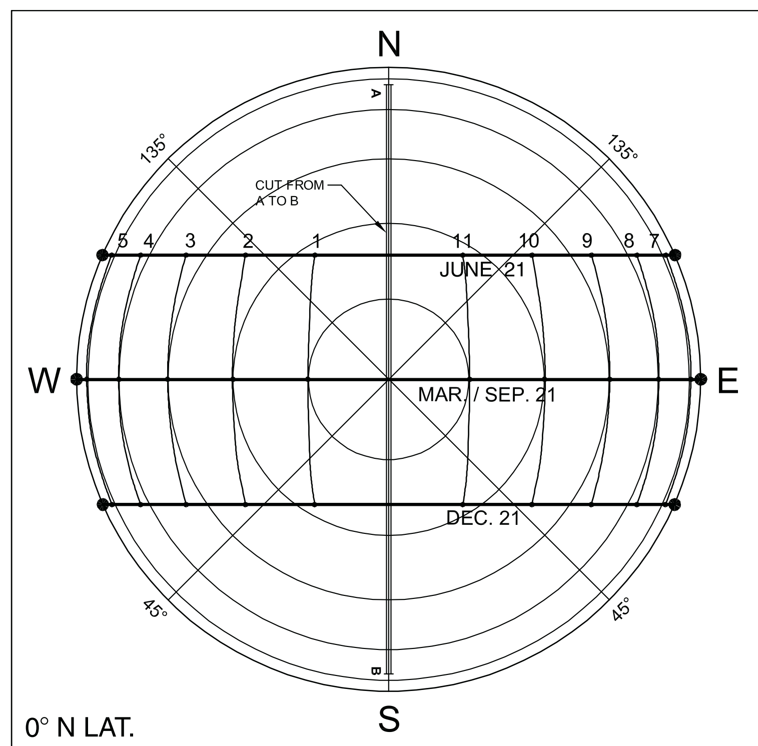
F.2 DIRECTIONS FOR CONSTRUCTING A SUN-PATH MODEL

Materials List

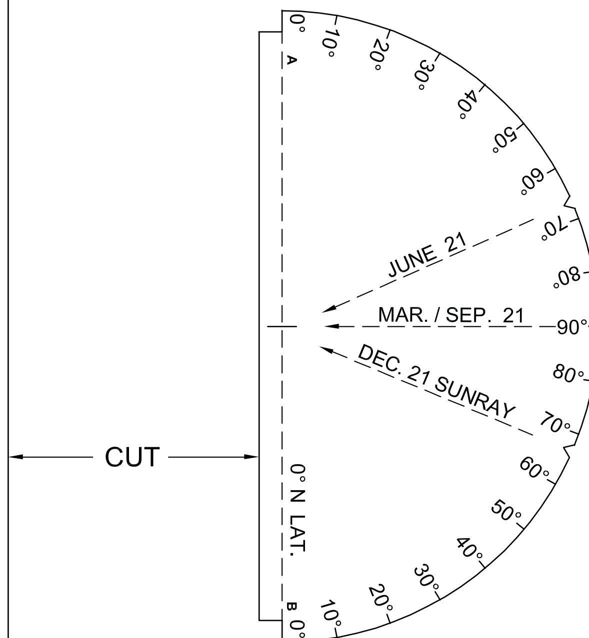
1. A piece of foam-core board that is slightly larger than the horizontal projections on the following pages. The board should be at least ¼ in. (65 mm) thick.
2. A piece of stiff, clear plastic film as large as the support quadrant. Acetate works well.
3. Three pipe cleaners, or two chenille pieces (available in hobby and craft stores), or about 18 inches (45 cm) of soft wire, such as copper or aluminum.

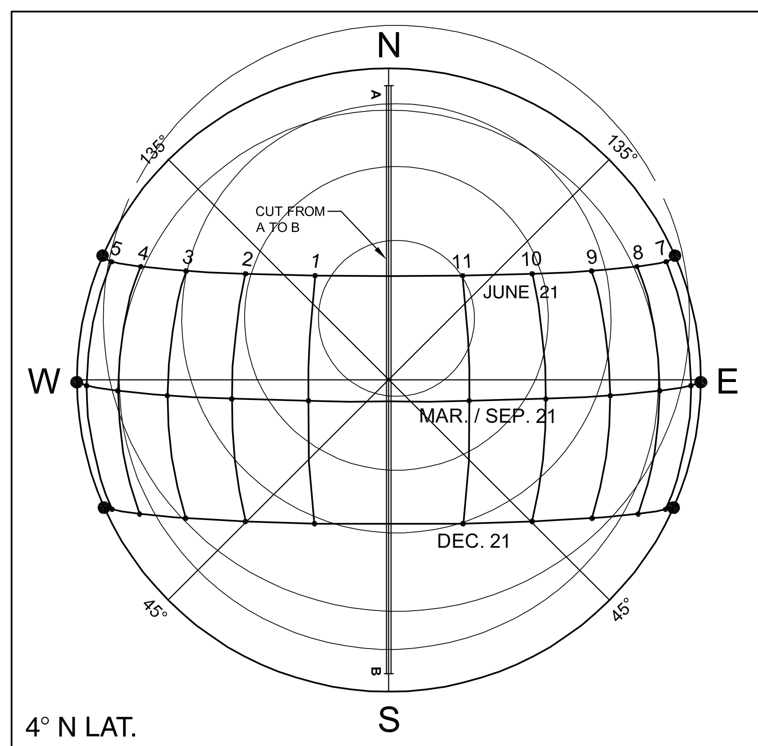
Procedure

1. To make the base, photocopy the orthographic projection closest to the latitude of interest and glue it on a piece of foam board of the same size.
2. Cut a deep slit from A to B on the north–south line of the projections.
3. Trace the support quadrant on a piece of fairly stiff clear plastic film.
4. Cut out the support quadrant and be sure to cut the three little notches where indicated.
5. Place the support quadrant in the slit so that marks A and B on the quadrant line up with marks A and B on the base.
6. Use a pushpin or sharp pencil to make holes at the sunrise and sunset points for each of the three sun paths. The holes should pass all the way through the base and be angled in the direction of the sun paths.
7. Insert one end of a pipe cleaner or wire in the sunrise hole for June 21. Bend it across the support quadrant and insert the other end in the sunset hole. Pull the pipe cleaner down until it rests in the top notch of the support quadrant. Repeat this procedure for the other two sun paths. Note that the three pipe cleaners should form segments of parallel circles.
8. Glue the pipe cleaners in place and trim off the excess from the bottom of the base.
9. Place a small balsa wood block (less than ¼ in. [65 mm] on a side) in the center to represent a building.

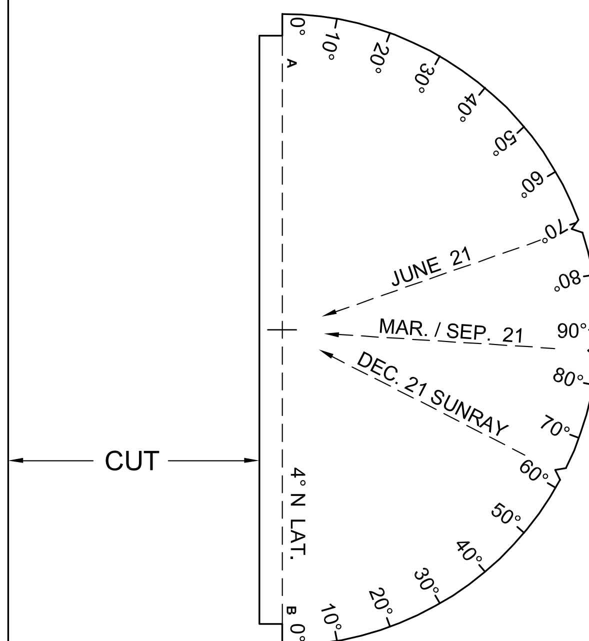

N
S
W
E
135°
135°
45°
45°
CUT FROM
A TO B
A
B
5 4 3 2 1 11 10 9 8 7
JUNE 21
MAR. / SEP. 21
DEC. 21
0° N LAT.

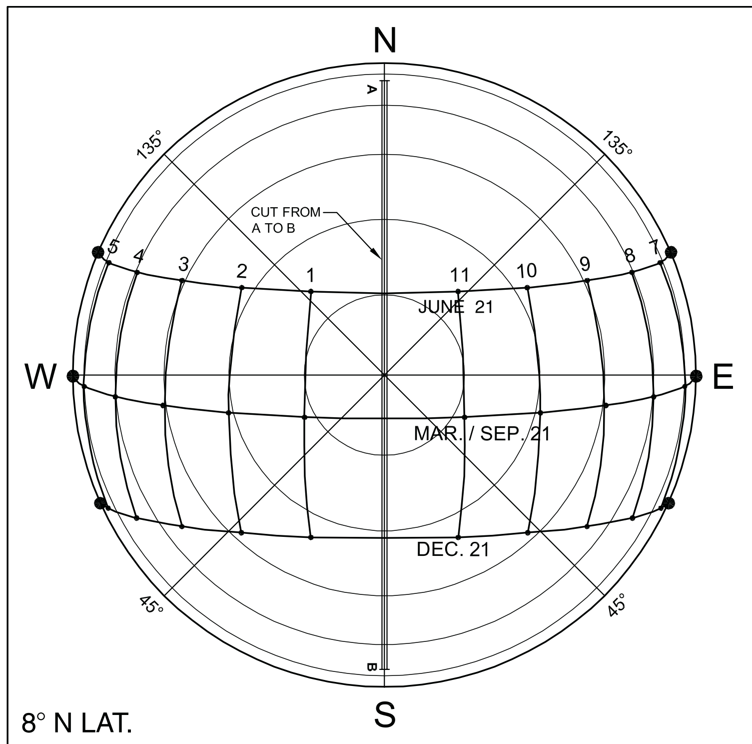
CUT

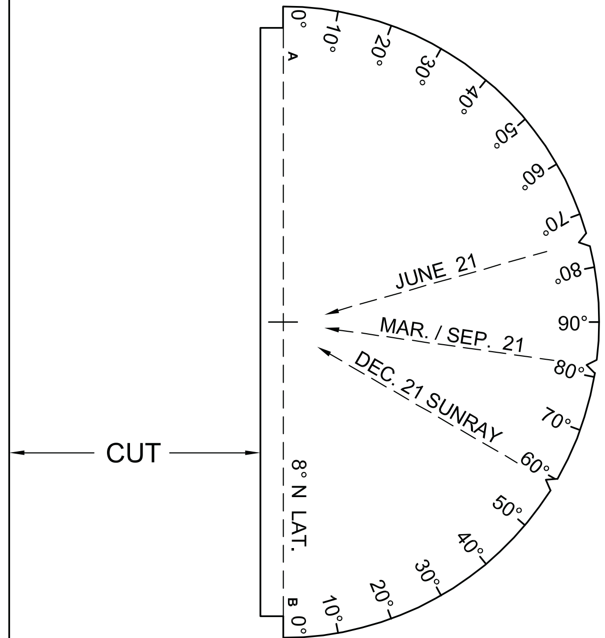

JUNE 21
MAR. / SEP. 21
DEC. 21 SUNRAY
0° N LAT.
A
B

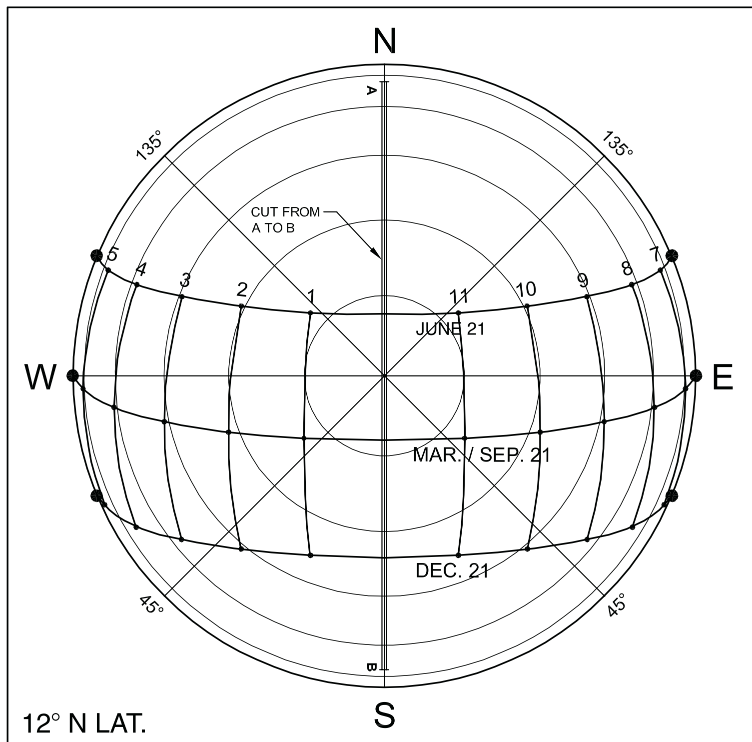

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135°
45°
45°
CUT FROM
A TO B
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B
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JUNE 21
MAR. / SEP. 21
DEC. 21
4° N LAT.

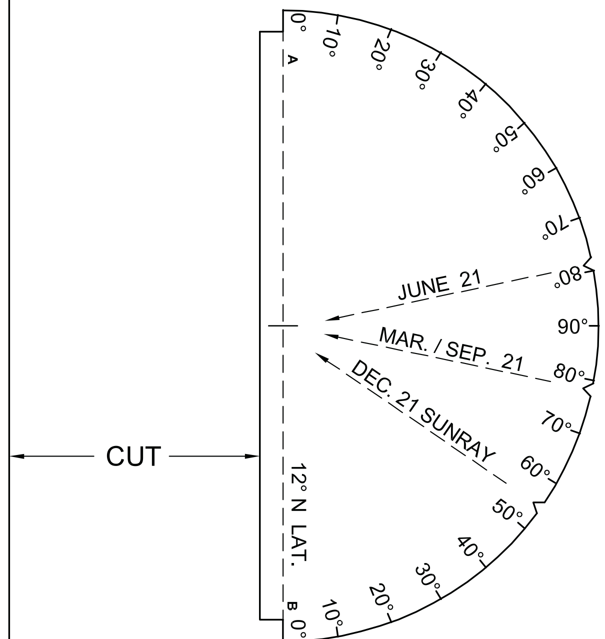
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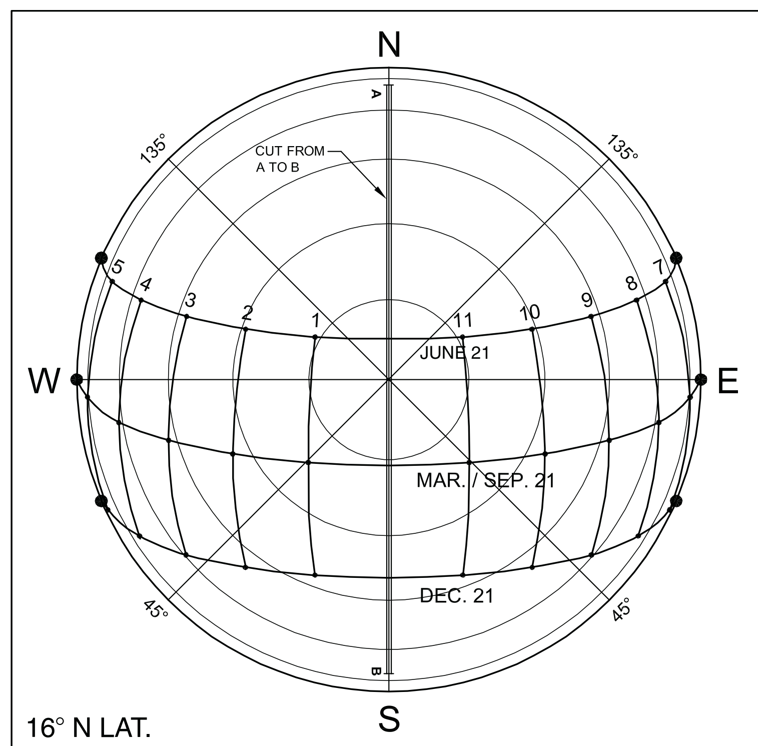

JUNE 21
MAR. / SEP. 21
DEC. 21 SUNRAY
4° N LAT.
A
B


N
S
W
E
135°
135°
45°
45°
CUT FROM A TO B
A
B
5
4
3
2
1
11
10
9
8
7
JUNE 21
MAR. / SEP. 21
DEC. 21
8° N LAT.

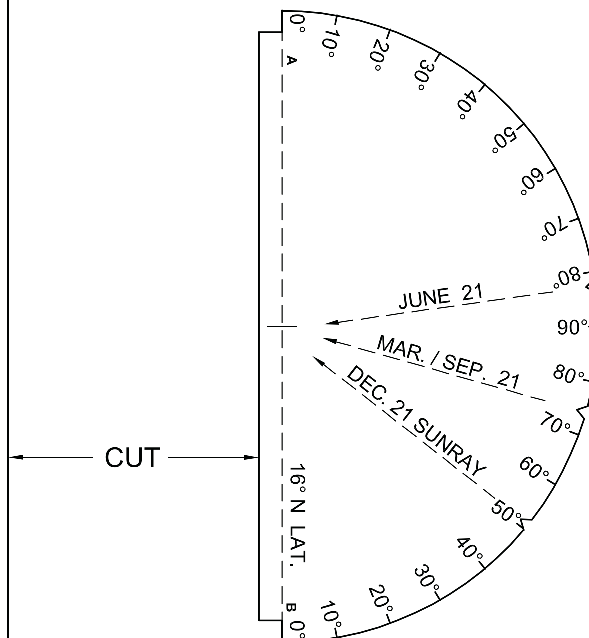

CUT
JUNE 21
MAR. / SEP. 21
DEC. 21 SUNRAY
8° N LAT.

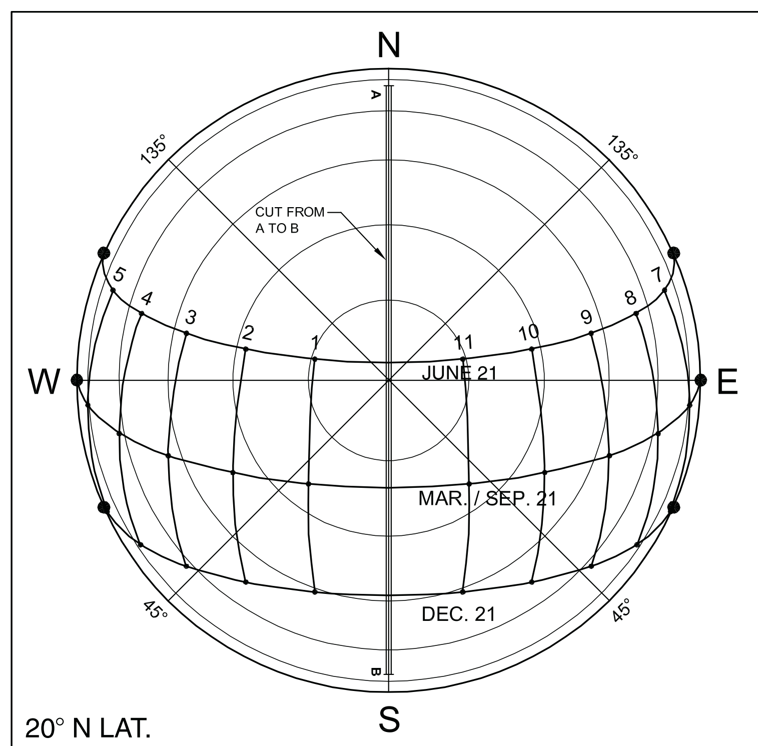

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135°
135°
45°
45°
CUT FROM A TO B
A
B
5
4
3
2
1
11
10
9
8
7
JUNE 21
MAR. / SEP. 21
DEC. 21
12° N LAT.


CUT
JUNE 21
MAR. / SEP. 21
DEC. 21 SUNRAY
12° N LAT.

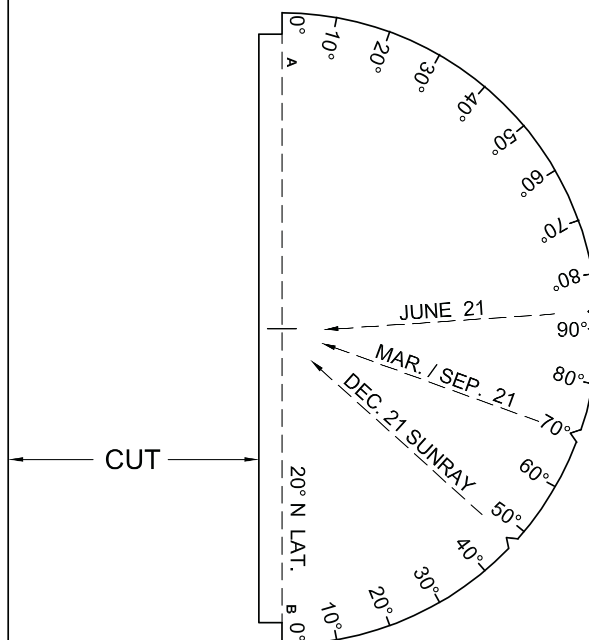

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135°
135°
45°
45°
CUT FROM
A TO B
A
B
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4
3
2
1
11
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9
8
7
JUNE 21
MAR. / SEP. 21
DEC. 21
16° N LAT.

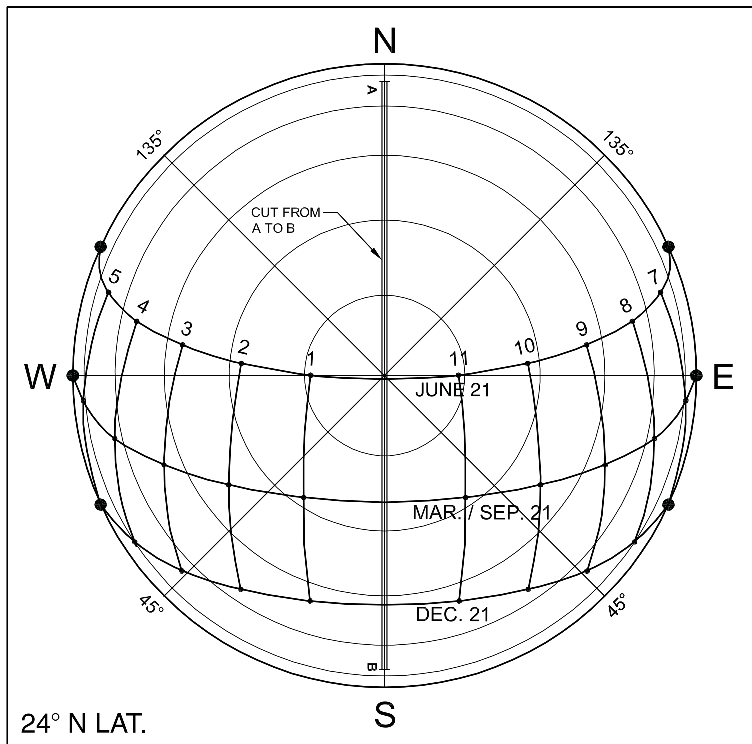
CUT


JUNE 21
MAR. / SEP. 21
DEC. 21 SUNRAY
16° N LAT.

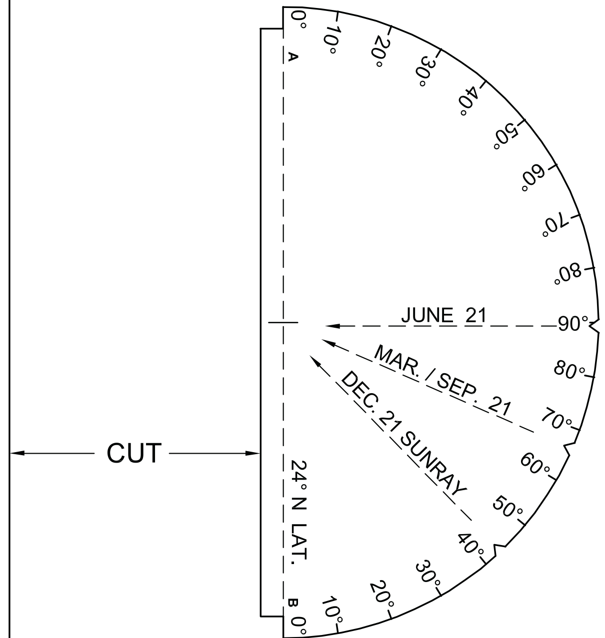

N
S
W
E
135°
135°
45°
45°
CUT FROM
A TO B
A
B
5
4
3
2
1
11
10
9
8
7
JUNE 21
MAR. / SEP. 21
DEC. 21
20° N LAT.

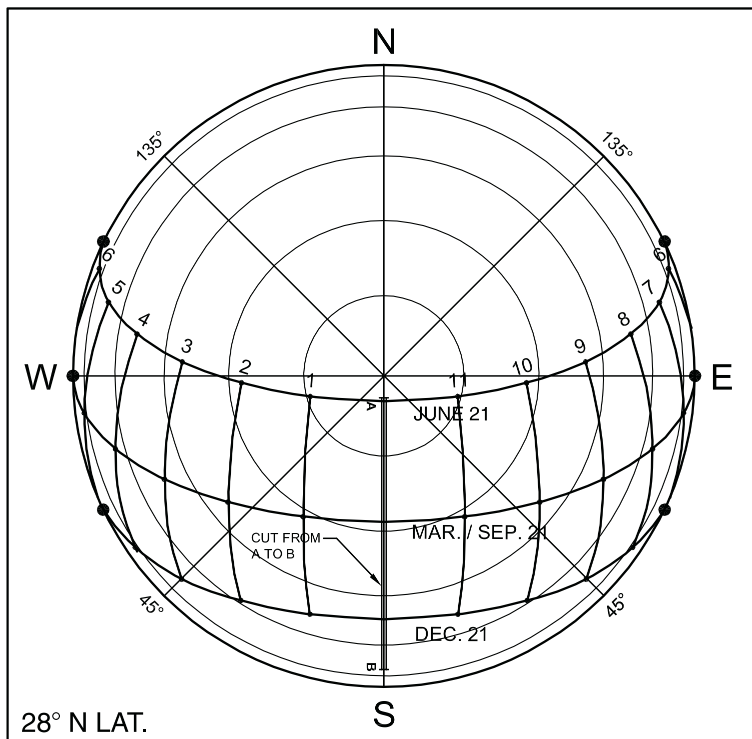
CUT


JUNE 21
MAR. / SEP. 21
DEC. 21 SUNRAY
20° N LAT.

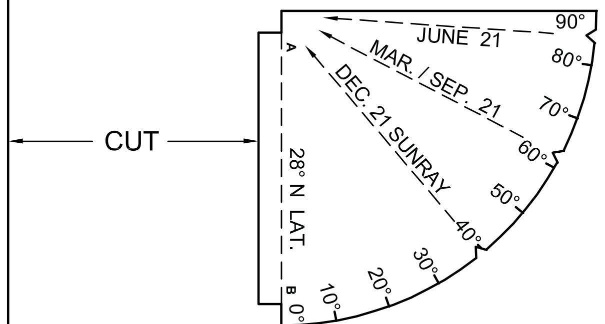

N
S
W
E
135°
135°
45°
45°
CUT FROM
A TO B
JUNE 21
MAR. / SEP. 21
DEC. 21
1
2
3
4
5
7
8
9
10
11
24° N LAT.

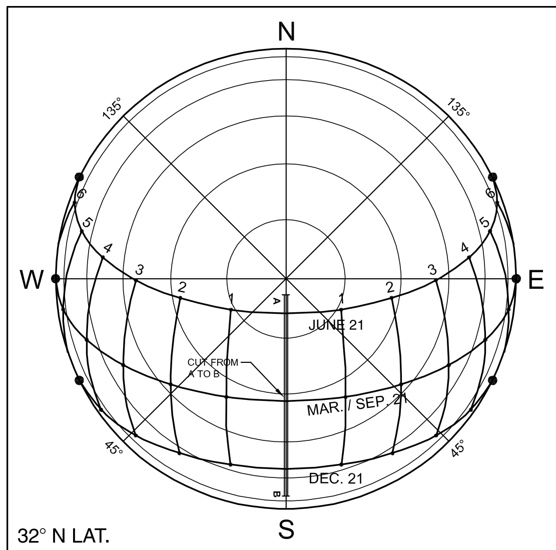
CUT


JUNE 21
MAR. / SEP. 21
DEC. 21 SUNRAY
24° N LAT.
0°
10°
20°
30°
40°
50°
60°
70°
80°
90°

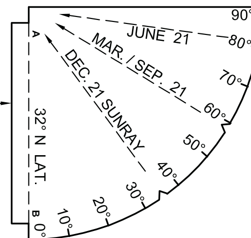

N
S
W
E
135°
135°
45°
45°
CUT FROM
A TO B
JUNE 21
MAR. / SEP. 21
DEC. 21
1
2
3
4
5
6
7
8
9
10
11
28° N LAT.

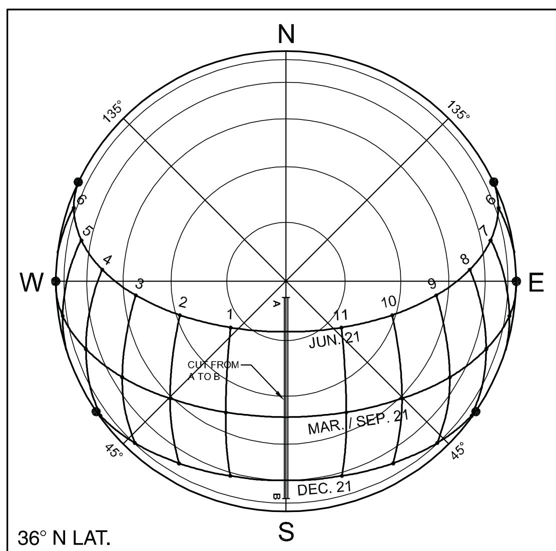
CUT


JUNE 21
MAR. / SEP. 21
DEC. 21 SUNRAY
28° N LAT.
0°
10°
20°
30°
40°
50°
60°
70°
80°
90°

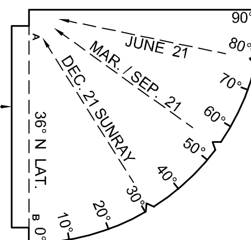

N
135°
135°
W
E
JUNE 21
CUT FROM
A TO B
MAR. / SEP. 21
45°
45°
DEC. 21
S
32° N LAT.

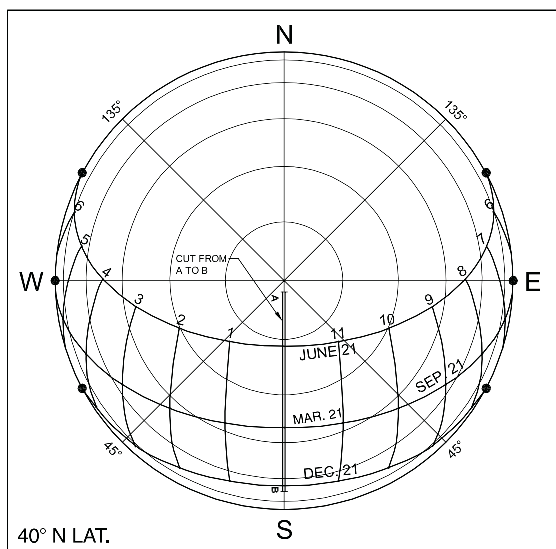
CUT


90°
JUNE 21
80°
MAR. / SEP. 21
70°
DEC. 21 SUNRAY
60°
50°
40°
30°
20°
10°
0°
32° N LAT.

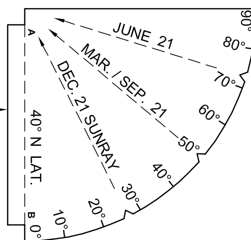

N
135°
135°
W
E
JUN. 21
CUT FROM
A TO B
MAR. / SEP. 21
45°
45°
DEC. 21
S
36° N LAT.

CUT


90°
JUNE 21
80°
MAR. / SEP. 21
70°
DEC. 21 SUNRAY
60°
50°
40°
30°
20°
10°
0°
36° N LAT.

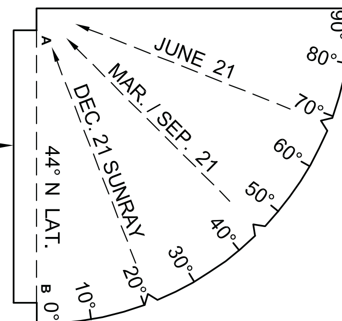

N
135°
135°
W
E
CUT FROM
A TO B
JUNE 21
SEP 21
MAR. 21
45°
45°
DEC. 21
S
40° N LAT.

CUT


90°
JUNE 21
80°
MAR. / SEP. 21
70°
DEC. 21 SUNRAY
60°
50°
40°
30°
20°
10°
0°
40° N LAT.

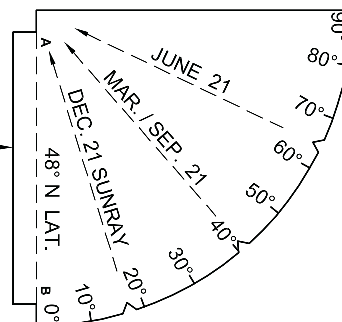
N
135° 135°
W E
CUT FROM A TO B
JUNE 21
MAR. / SEP. 21
DEC. 21
45° 45°
S
44° N LAT.

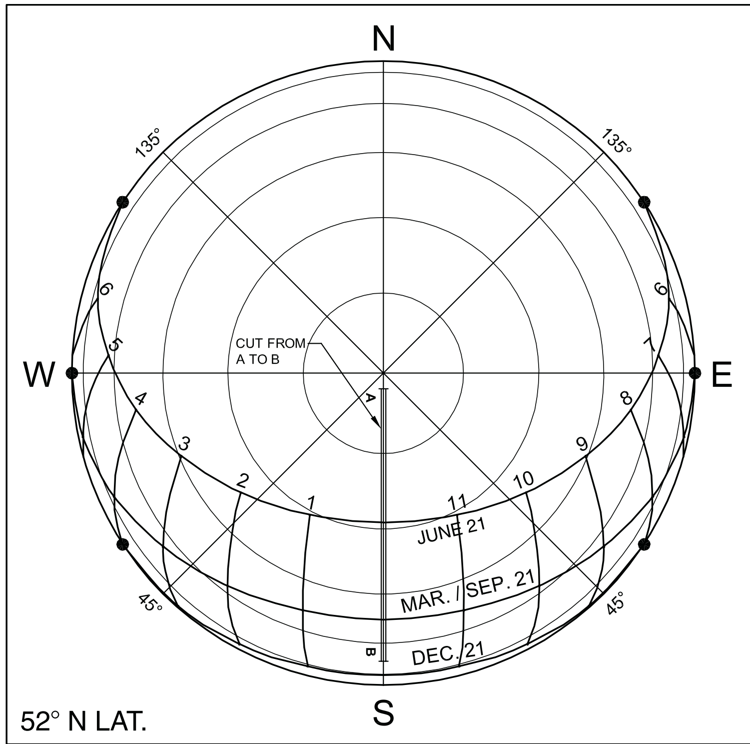

CUT



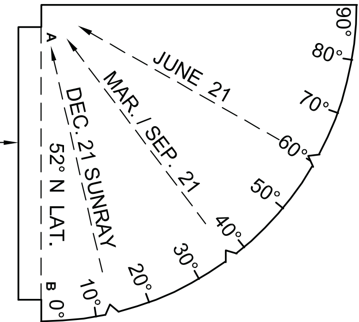
N
135° 135°
W E
CUT FROM A TO B
JUNE 21
MAR. / SEP. 21
DEC. 21
45° 45°
S
48° N LAT.

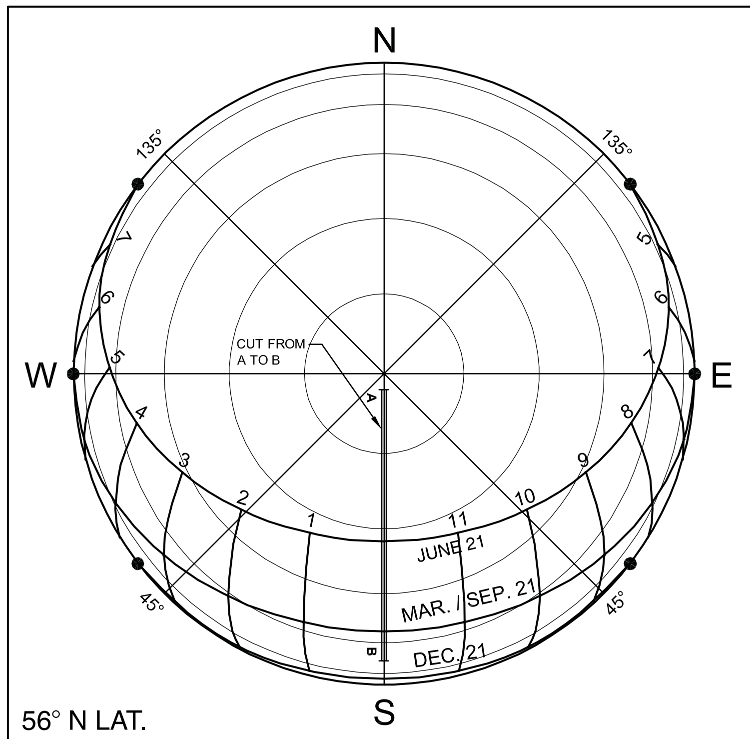

CUT



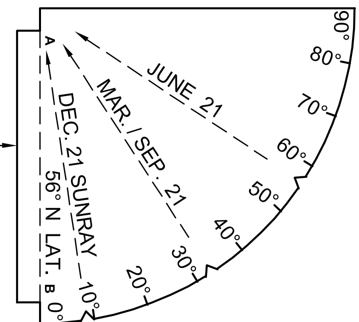

N
S
W
E
135°
135°
45°
45°
CUT FROM
A TO B
A
B
JUNE 21
MAR. / SEP. 21
DEC. 21
52° N LAT.

CUT


JUNE 21
MAR. / SEP. 21
DEC. 21 SUNRAY
52° N LAT.
90°
80°
70°
60°
50°
40°
30°
20°
10°
0°

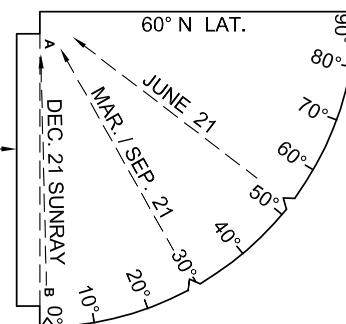

N
S
W
E
135°
135°
45°
45°
CUT FROM
A TO B
A
B
JUNE 21
MAR. / SEP. 21
DEC. 21
56° N LAT.

CUT


JUNE 21
MAR. / SEP. 21
DEC. 21 SUNRAY
56° N LAT.
90°
80°
70°
60°
50°
40°
30°
20°
10°
0°

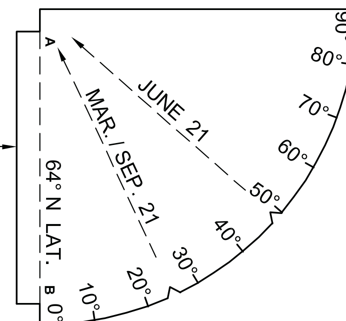
N
135° 135°
7 5
6 6
W 5 CUT FROM A TO B 7 E
A
4 8
3 9
2 10
1 11
JUNE 21
MAR. / SEP. 21
B
DEC. 21
45° 45°
S
60° N LAT.

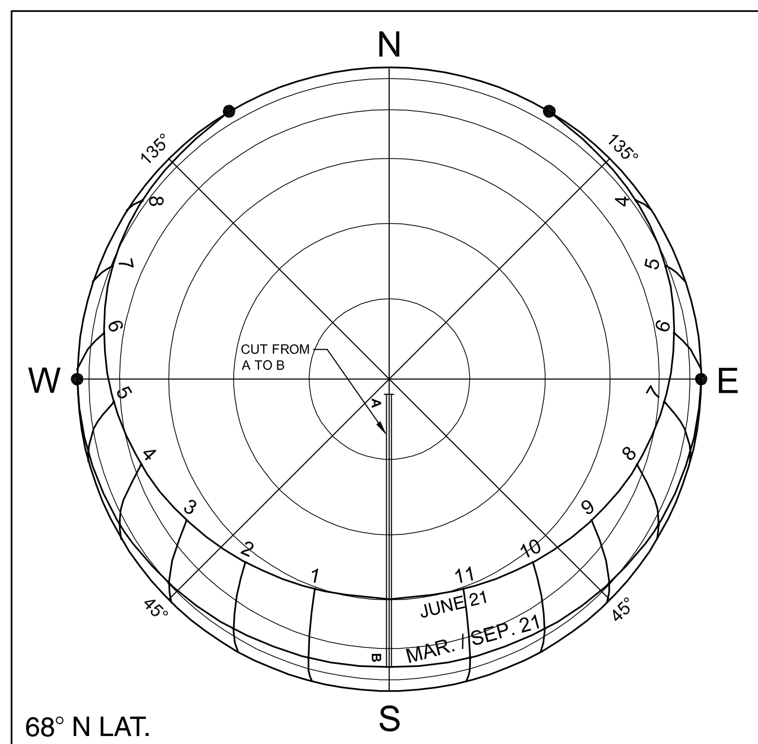


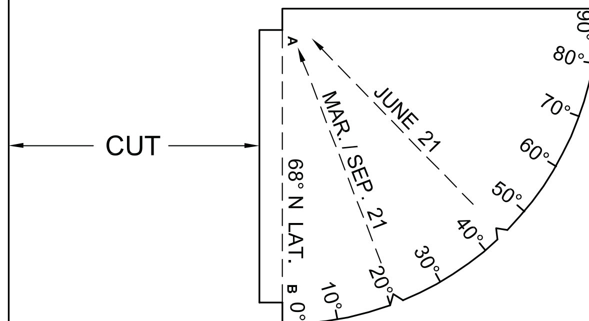


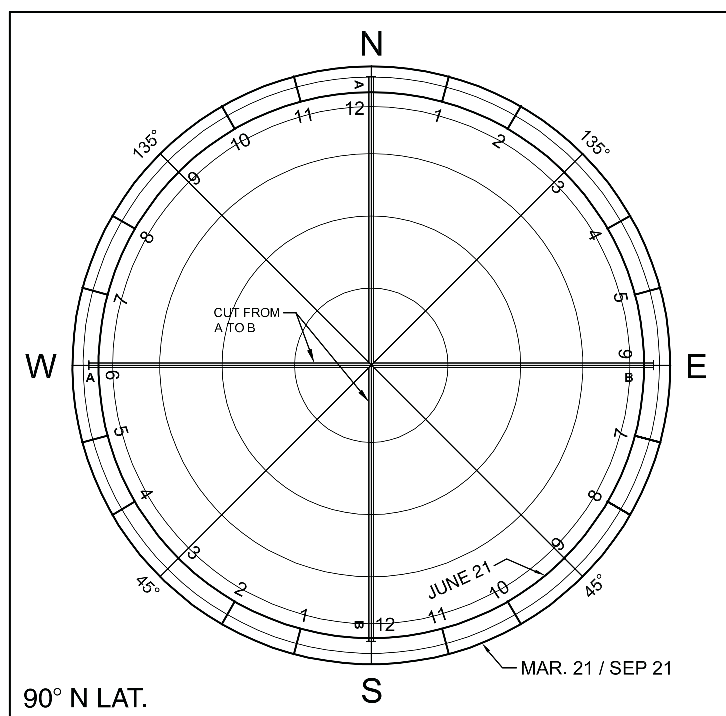
N
135° 135°
7 5
6 6
W 5 CUT FROM A TO B 7 E
A
4 8
3 9
2 10
1 11
JUNE 21
MAR. / SEP. 21
B
45° 45°
S
64° N LAT.

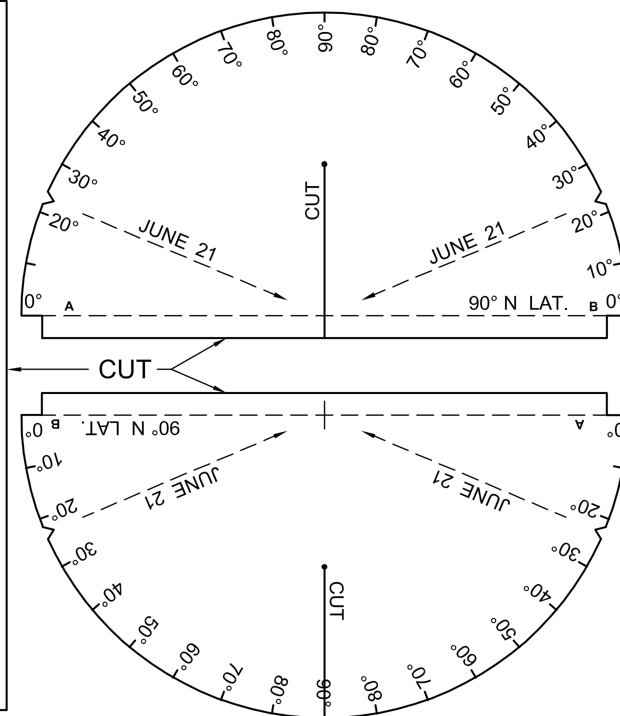





N
S
W
E
135°
135°
45°
45°
CUT FROM
A TO B
JUNE 21
MAR. / SEP. 21
68° N LAT.


CUT
JUNE 21
MAR. / SEP. 21
68° N LAT.


N
S
W
E
135°
135°
45°
45°
CUT FROM
A TO B
JUNE 21
MAR. 21 / SEP 21
90° N LAT.


CUT
JUNE 21
JUNE 21
90° N LAT.

APPENDIX G

The Water Table for Ventilation Studies

G.1 INTRODUCTION

The water table illustrated in Figure 10.7d can simulate air flowing through a building. Streams of colored water simulate in slow motion the smoke streams in a wind tunnel or in an actual building (Fig. G.1).

Water is allowed to flow evenly across the table on which a ¾ in. (2 cm) deep horizontal or vertical slice of a model is placed. Water will flow through openings in the model representing windows. After a steady-state flow has been achieved, dyed water is poured into the color tray to form parallel color streams. As these dye streams pass through the model, it is possible to determine where water is moving and where it is stagnant. A photo is then taken to document the ventilation pattern.

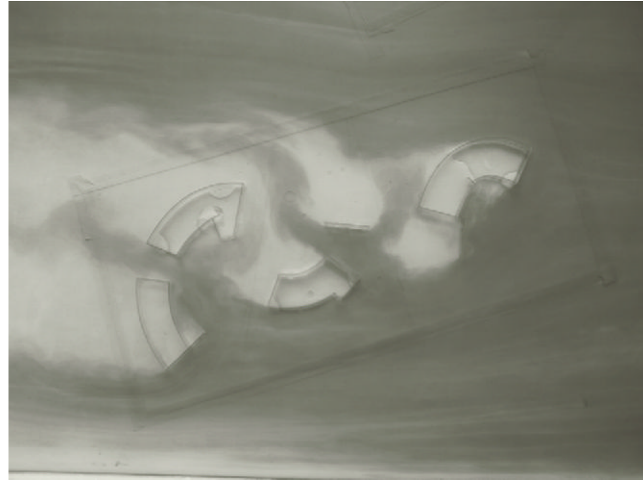


Figure G.1 Colored parallel streams of water flow through the shallow model of a building being tested on the water table at Chiang Mai University in Thailand. The water passing through the model closely simulates air flowing through a building. (Courtesy the 5th year project on Water Table Experiment, Chiang Mai University, Thailand.)

G.2 CONSTRUCTION OF A WATER TABLE

A sturdy table is necessary so that the water table surface can be completely flat. Also, adjustable legs allow the table to be leveled (Fig. G.2a) side by side and to have a slight slope in the long direction for the water to flow slowly.

The trough on one short end is filled with tap water, while the trough on the other short end is connected to a drain (Fig. G.2b). A valve allows the creation of a thin layer of water (about 2–3 mm) flowing across the table. A color tray spanning the short dimension of the water table is resting about 5 mm above the water flowing across the table (G.2c). At the appropriate time, colored water is poured into

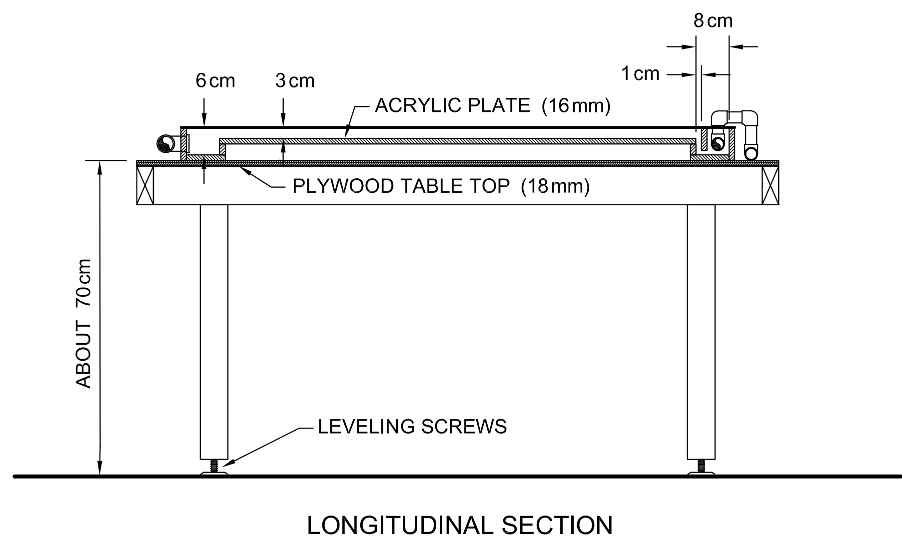


Figure G.2a Longitudinal section of the water table.

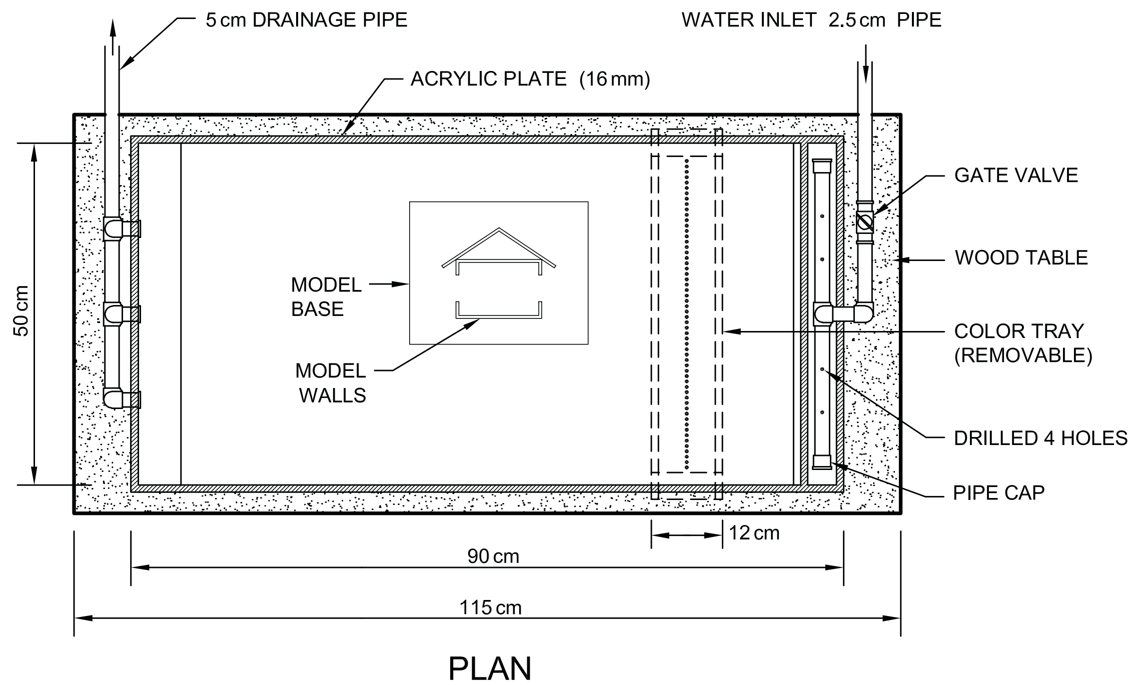


Figure G.2b Plan view. Note how the color tray rests on the edges of the water table.

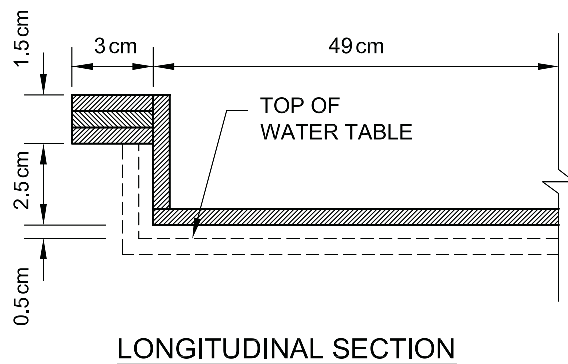


Figure G.2c Detail of color tray.

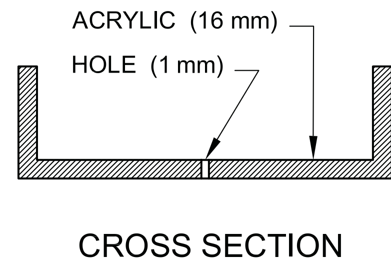


Figure G.2d The cross section of the color tray is shown. Drill 1 mm holes evenly along the center with a spacing of 10 mm.

this tray. The colored water leaks out of tiny 1 mm equally spaced holes on the bottom of the tray (G.2d) so that parallel color streams are created in the flowing water.

The horizontal model slice of the building design to be tested consists of walls about 2 cm high glued to a thin sheet of plastic about 0.5 mm thick (Fig. G.2e).

Potassium permanganate makes a very good dye.

The information for this water table appendix was furnished by Prof. Ruht Tantachamroon of Chiang Mai University, Thailand.

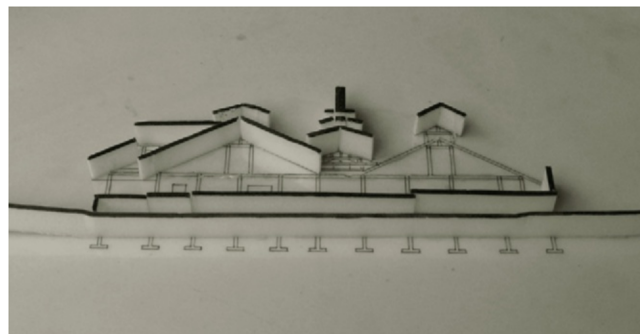


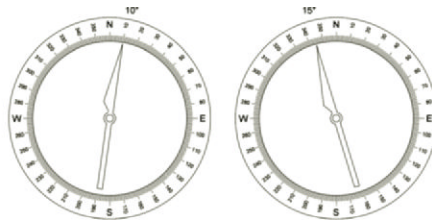
Figure G.2e The model to be tested consists of a 2 cm deep slice of the building plan being analyzed. The horizontal or vertical slice is made where the critical windows are located.

APPENDIX H

Site Evaluation Tools

H.1 INTRODUCTION

As described in Section 6.16, site evaluation tools can describe how much the sun is blocked from the building site by trees, neighboring buildings, landforms, etc. Four different tools are described below. The first two are commercially available, while the second two are do-it-yourself models. Make the sun locator (Fig. H.4) for a quick but approximate site evaluation tool, or make the solar site evaluator (Fig. H.5a) for a much more precise site analysis tool. For any of these site evaluation tools to be accurate, they must be aligned with the geographic (true) North Pole. Since they are all supplied with a compass, an adjustment must be made because the magnetic north and true north can be off by more than 15°. The declination or correction angle can be found at www.magnetic-declination.com for any town or city all over the world. As Figure H.1 shows, the declination angle can be either to the east or west of north on the compass. The declination angle found at the Web site also specifies which side of north the declination angle must be added to the compass north.



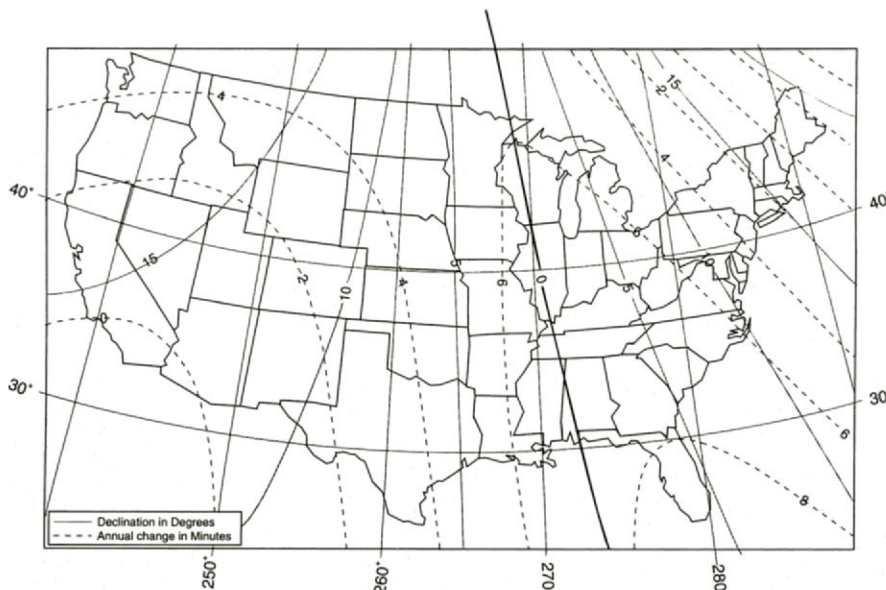


Figure H.1 The magnetic declination map of the United States. True south and magnetic south are only aligned along the 0° declination line. Everywhere else, the compass must be rotated east or west according to the declination. For example, in the middle of Massachusetts, the compass must be rotated clockwise 15°. Because the lines of magnetic declination shift with time, it is best to get the latest information from www.magnetic-declination.com. (Data from 1995 U.S. Geological Survey. Map courtesy of North Carolina Solar Center.)

H.2 THE SOLAR PATHFINDER

All site evaluation tools superimpose the sun paths for that site (i.e., latitude) on top of a view of the actual site. By looking down onto the Solar Pathfinder, one can see a 360° panoramic image of the site reflected off the clear plastic dome (Fig. H.2). At the same time, one can see through the dome to view the sun-path mask placed under the dome. Thus, one sees the sun paths superimposed on a view of the site. The Solar Pathfinder comes with masks for various latitudes. Software is also available to make this tool even more valuable. For more information, go to www.solarpathfinder.com or call (317) 501-2529.

H.3 THE SUNEYE

The SunEye is a handheld electronic tool that instantly measures shading

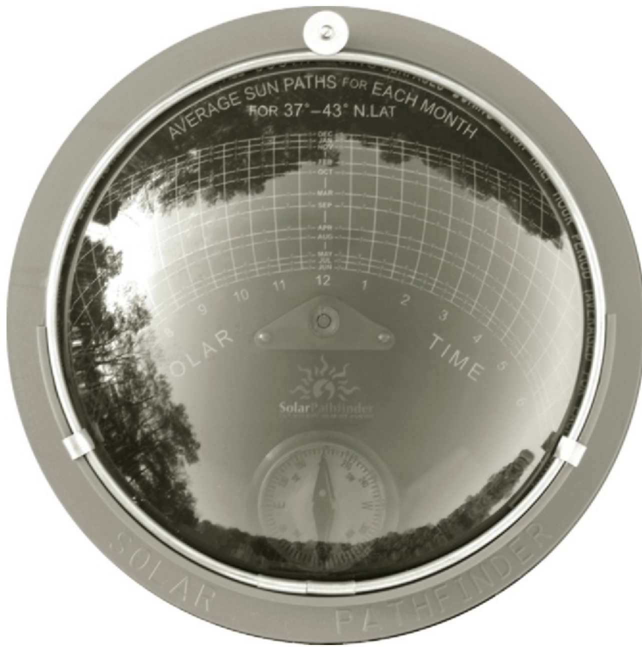


Figure H.2 The Solar Pathfinder solar site-evaluation tool. (Courtesy Solar Pathfinder, 3953 Marsh Greek Road, Linden, TN 37096; 317–501-2529.)



Figure H.3 The SunEye solar site-evaluation tool. (Courtesy Solmetric.)

and solar access data for a particular location. With the press of a button, the user can see when and where shadows will occur throughout the day and year. The SunEye is used by solar panel installers to optimize the placement and orientation of solar panels, and by green architects and landscape designers.

The integrated digital camera and fish-eye lens capture an image of the entire horizon in 360° (Fig. H.3). Onboard electronics do the following: superimpose the paths of the sun throughout the year based on latitude, detect shade-causing obstructions, and calculate the annual, monthly, daily, and hourly solar access. The SunEye can store more than fifty site readings, transfer data to a PC for further analysis, and export data into a printable report. The built-in edit tool can be used to easily simulate removal or trimming of shade-causing trees.

Because the latest version has a VSP port, it can be read remotely when raised on a pole to a height of about 18 feet (5.4 m). Until this development, all site evaluation tools could only evaluate the spot where a person was holding the tool. Thus, to evaluate the solar access of the roof, the tool had to be taken to the roof, and in the case of a building yet to be built, these tools could be used only with great difficulty.

The SunEye is sustainably manufactured by Solmetric, incorporating a unique design that utilizes refurbished and recycled materials. For more information about Solmetric or the SunEye, go to www.solmetric.com.

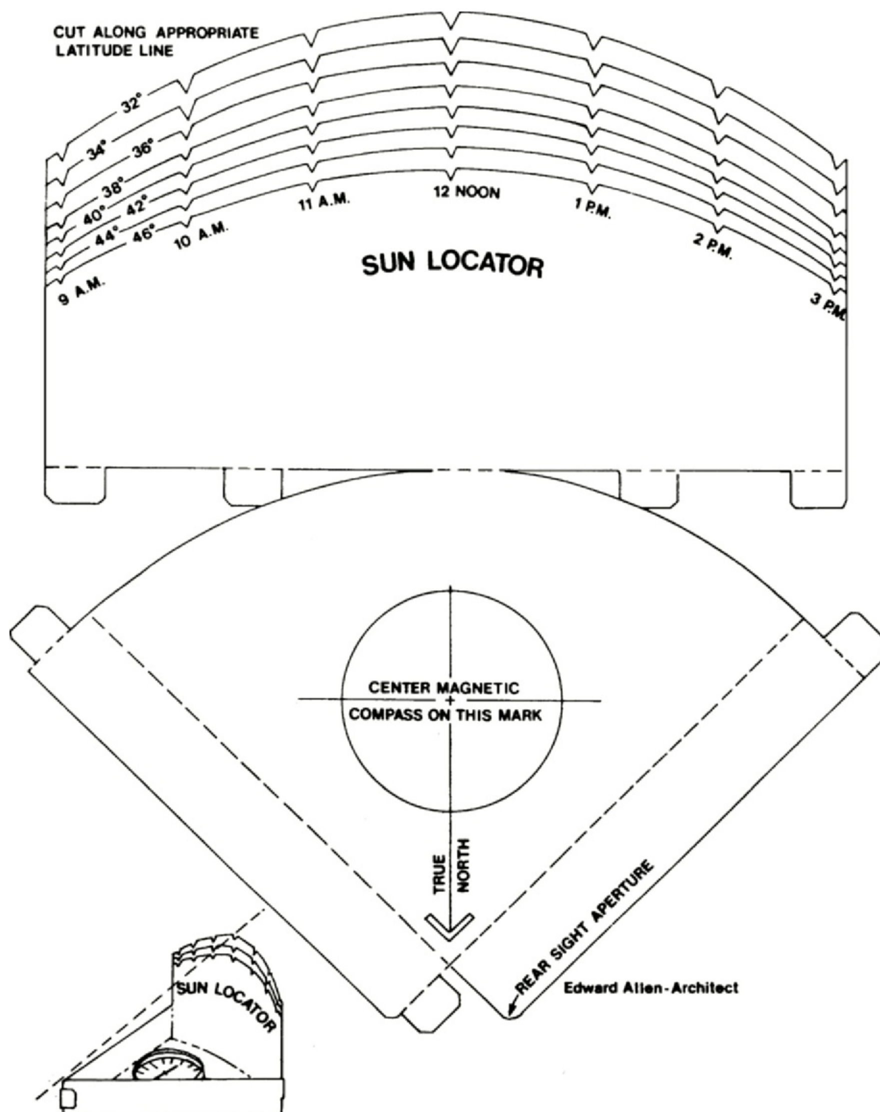


Figure H.4 The sun locator. (Courtesy Edward Allen and North Carolina Solar Center.)

H.4 THE SUN LOCATOR

Make an enlarged copy of the sun locator (Fig. H.4) and glue it to a cardboard backing. Trim along the line of the latitude nearest you. Place the locator in a level position at the area where the solar collectors or windows are to be mounted. Aim the tool to true south by using a compass and adjusting for the magnetic declination (Fig. H.1). View from the corner over the top of the latitude line from 9 A.M. to 3 P.M. solar time. This is the path the sun will take in midwinter. If more than 5 percent of the path is blocked, the site might need closer evaluation. Even tree branches without leaves can block a considerable amount of winter sunlight. Consider trimming them if necessary.

H.5 DO-IT-YOURSELF SOLAR SITE EVALUATOR*

The solar site evaluator consists of three parts: a semicircular wooden base, a clear plastic mask, and a removable wooden handle (see Fig. H.5a). The mask is held to the base via a Velcro™ strip for two reasons. The Velcro allows using different masks for different latitudes (4° intervals), and it makes the device easier to store and carry in a disassembled state. This solar site evaluator is fairly easy and quick to build and costs only about $20 in materials.

The dimensions, given in the I-P system, are for convenience only—slightly larger or smaller site evaluators will work equally well. The only critical consideration is to match the length of the semicircle of the base to the length of the mask so that east is on one end, south in the middle, and west on the other end. Also, because it is desirable to use a photographic tripod to hold the site evaluator, the T nut should be for a ¼ in. screw, which is the standard on all cameras.

Parts List

- pine board, 1 × 8 × 15 (nominal dimensions)
- wooden dowel, ¾ in. diameter minimum and 6 in. long
- sheet of clear acetate, 20 × 24 in., at least 0.005 in. thick
- compass (inexpensive kind)
- bull's-eye level
- T nut, ¼ in. diameter and ¾ in. long (see fig. H.5a)
- combination wood/machine screw, ¼ in. diameter and 1½ in. long
- strip of self-adhesive Velcro about 28 in. long and ¾ in. wide
- cotton swab (e.g., Q-Tip™)

Construction Process

Base

Since a 1 × 8 board has an actual width of only 7¼ in., cut a semicircle with a 7¼ in. radius from the board.

Drill a hole 2 in. from the middle of the straight edge of the base for mounting the T nut as shown in Figure H.5a. About ¼ in. from the middle of the straight edge, also drill a 3⁄32 in. hole. Insert a cotton swab in this hole in such a manner that the

*Adapted from the design by Daniel K. Reif (www.homeplanner.com) from his book *Solar Retrofit: Adding Solar to Your Home*, Brick House Publishing Co., Amherst, NH, 1981.

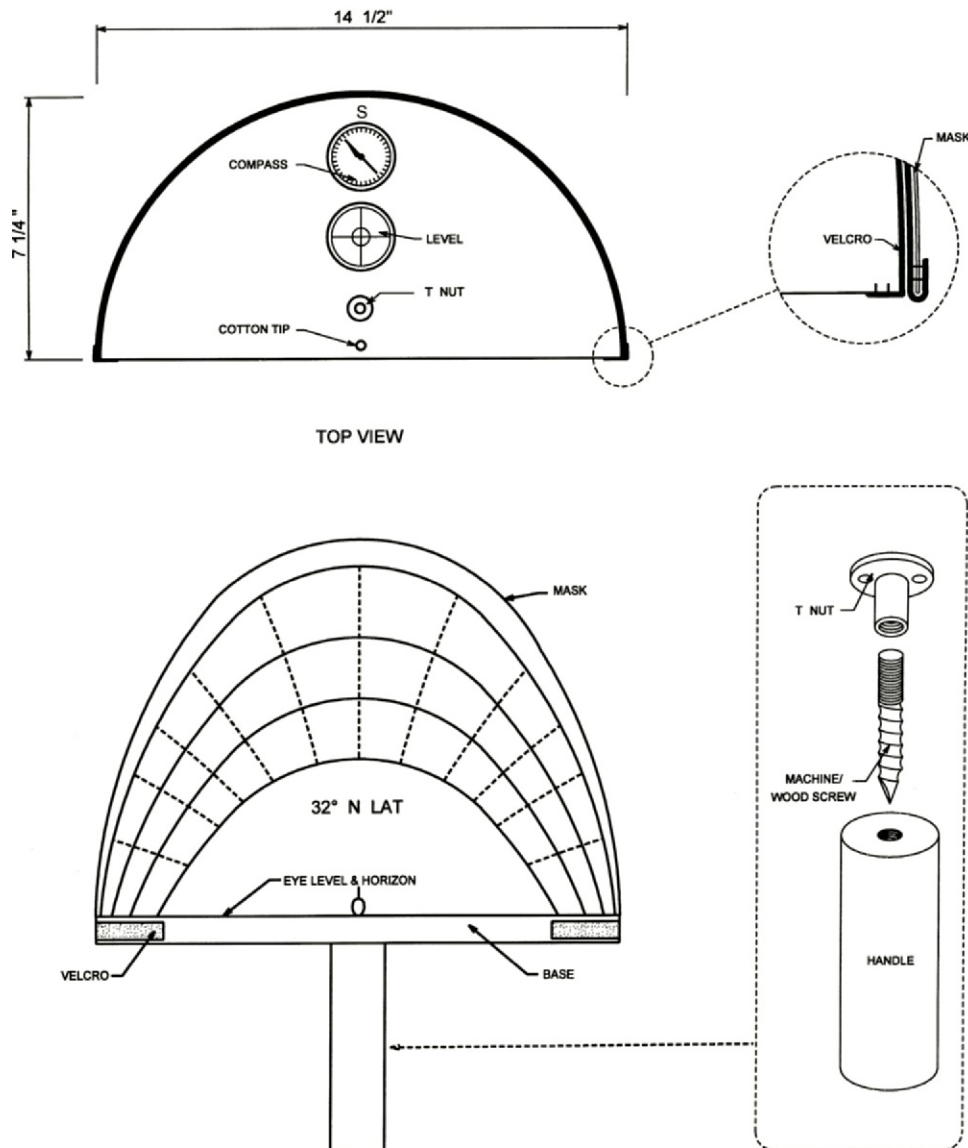


Figure H.5a The solar site evaluator.

top of the cotton tip is just above the base. The cotton swab is used as a sight in order to prevent potential damage to the eye. Next, glue a Velcro strip to the edge of the base. For better holding power, extend the Velcro around the base, as shown in the front view of Figure H.5a, and staple the Velcro at both ends. Finally, glue the compass and level to the top of the base, as shown in Figure H.5a. Make sure that south on the compass is aligned with south on the mask.

Handle

The handle is only needed if a camera tripod will not be available. If the handle will be needed, drill a 3⁄16 in. hole in one end of the wood dowel, and insert the combination wood/machine screw in such a manner that about ¾ in. of the machine screw sticks out of the dowel.

Masks for Latitudes 26° to 46°

Drawings of masks for five different latitudes (28°, 32°, 36°, 40°, and 44°) have been prepared and are shown in Figures H.5b to H.5f. Use the drawing that is less than 2° from the latitude desired. Enlarge it until the line marked 6 in. is full size or the length of the mask is the same as the semicircle of the wood base. Then transfer the lines onto a relatively stiff clear film, such as 0.005 in. (0.15 mm) thick acetate. Cut the film as shown, and apply along the bottom inside surface of the mask the ¾ in. self-adhesive Velcro strip that matches the one on the base. For

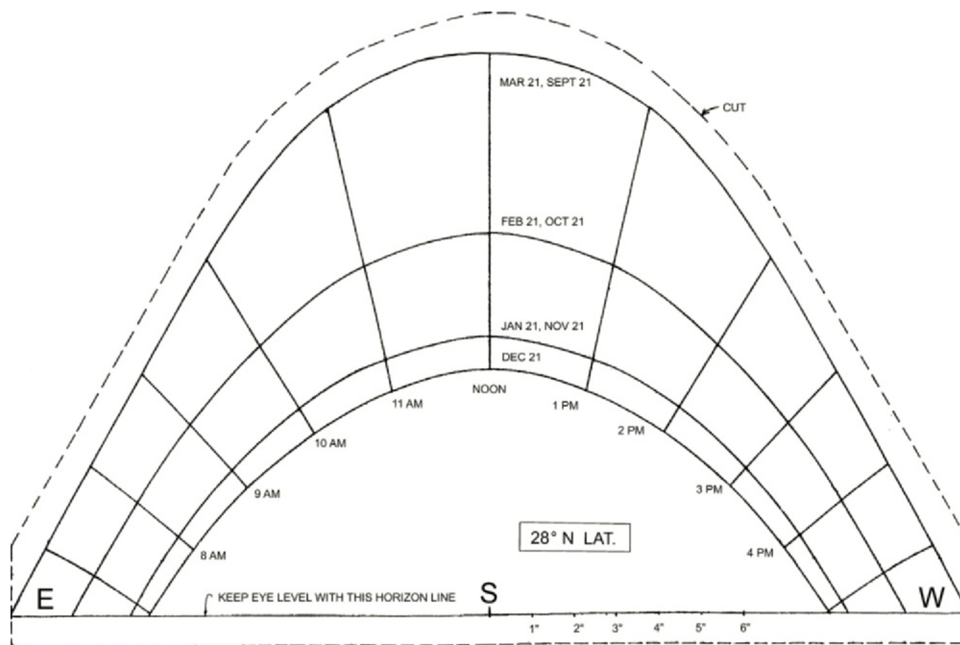


Figure H.5b The solar site evaluator mask for 28° N latitude.

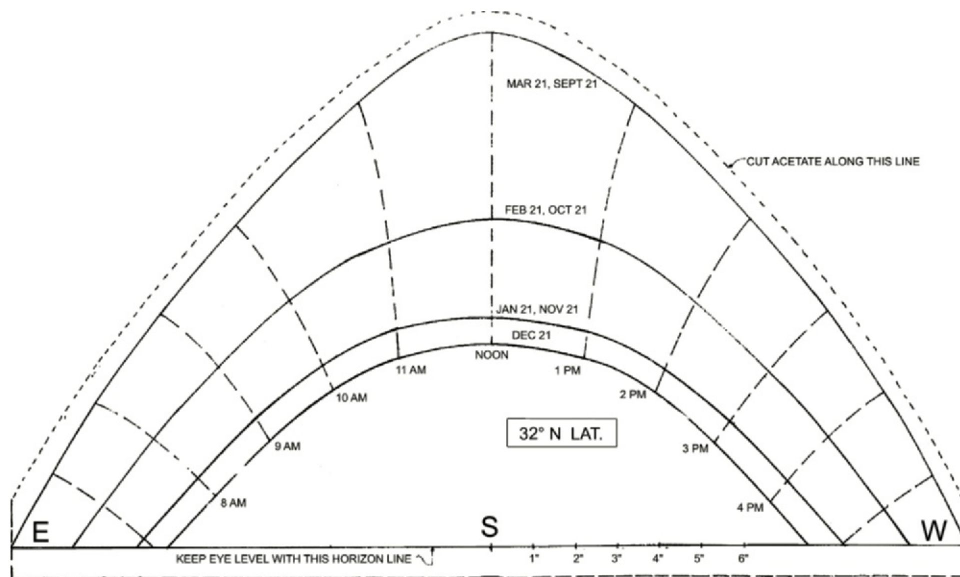


Figure H.5c The solar site evaluator mask for 32° N latitude.

extra strength, return the Velcro strip, as shown in the detail of Figure H.5a.

Masks for Latitudes Less Than 26° and More Than 46°

To make a mask for latitudes not given, draw the winter sun paths for the required latitude on a **full-scale** version of the altitude/azimuth graph shown in Figure H.5g. The altitude and azimuth angles for latitudes at 4° intervals are found in Appendix C of this book. Plot the points for each hour of the following sun paths: December 21, November/January 21, October/February 21, and March/September 21. Connect the points with solid lines to form the sun paths, and with dashed lines for the hours of the day to form a diagram like that in Figure H.5e. Be sure to label the mask for the latitude of its sun paths. Then trace it onto a sheet of transparent film as described above for "Masks for Latitudes 26° to 46°." These masks can also be generated by the program ClimateConsultant, which can be found at www.energy-design-tools.aud.ucla.edu/.

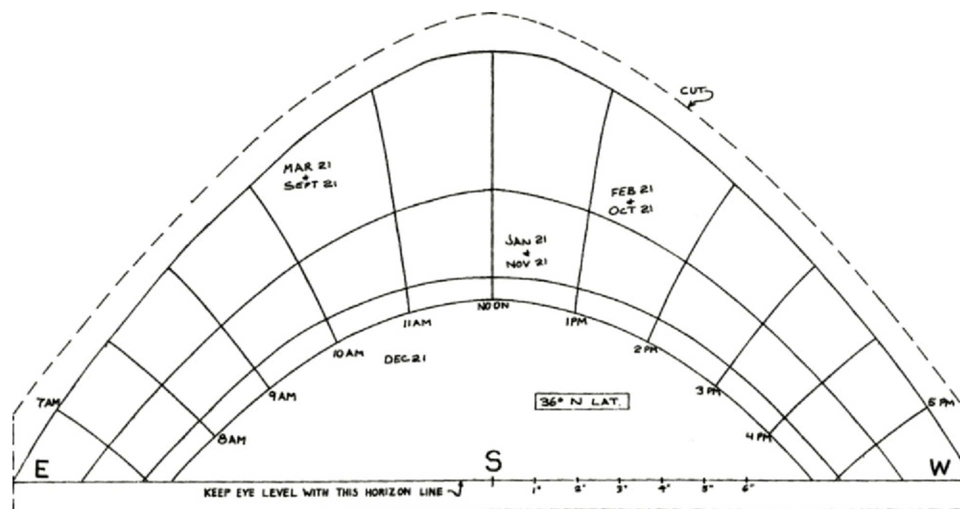


Figure H.5d The solar site evaluator mask for 36° N latitude.

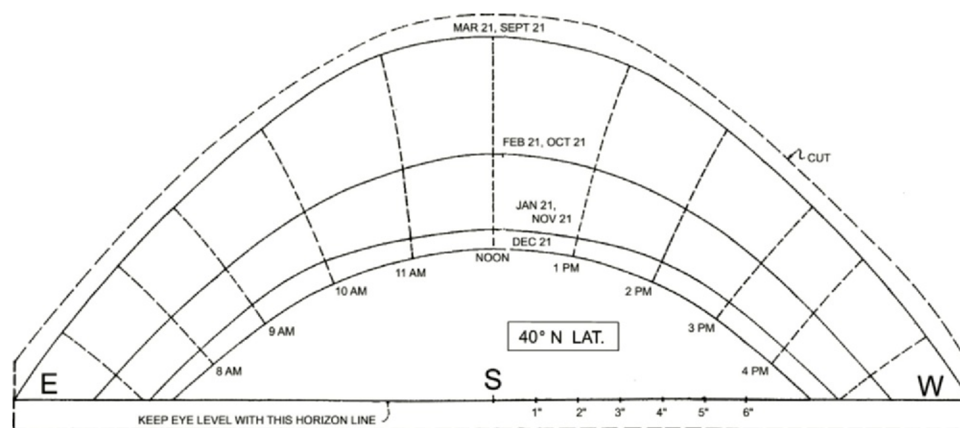


Figure H.5e The solar site evaluator mask for 40° N latitude.

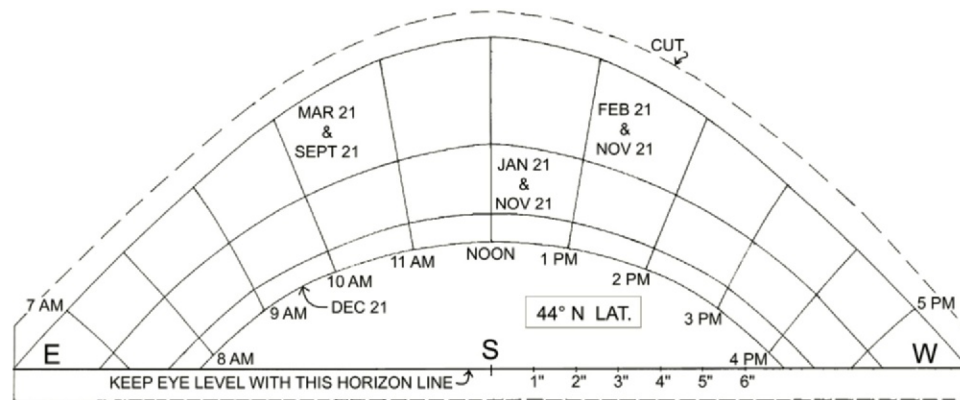


Figure H.5f The solar site evaluator mask for 44° N latitude.

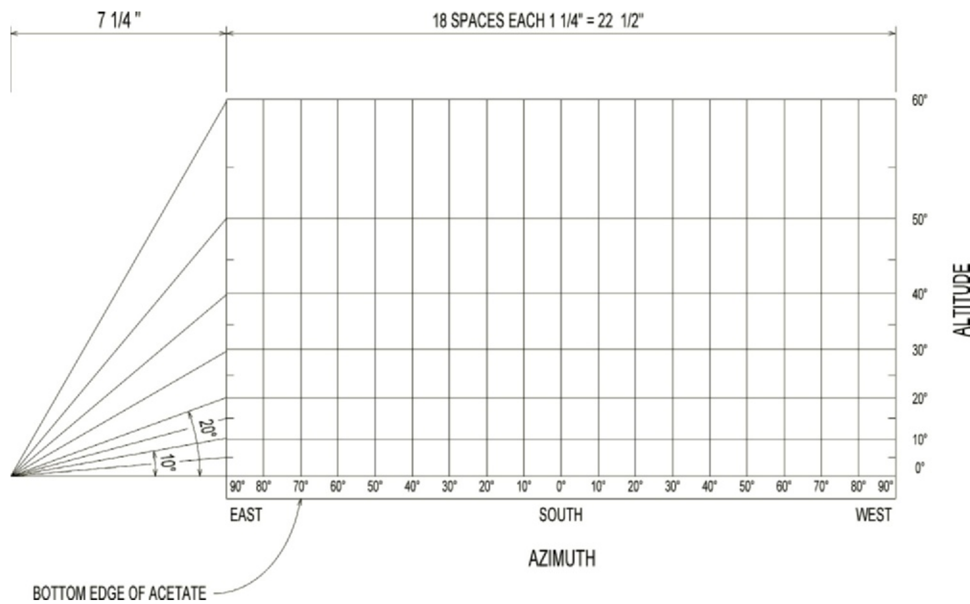


Figure H.5g The solar site evaluator altitude/azimuth graph.



Figure H.5h Mounting the solar site evaluator on a camera tripod is especially helpful when tracing a horizon profile.

Using the Solar Site Evaluator

This tool enables the user to determine when and how much a certain location will be shaded from the sun. This is possible because when one looks through the evaluator at the actual site, the sun-path diagrams are superimposed on the view of the site (see Figs. H.5h and 6.16). It is immediately obvious which trees or buildings are blocking the solar window and by how much. A record of the site condition can be traced on an overlay on the mask (see Fig.6.12c). This tool is best used on nonwindy overcast days or on sunny days before 9 A.M. and after 3 P.M. so that it is not necessary to look directly into the sun, especially in the winter.

Steps for Use

1. Attach the mask to the base by means of the Velcro strip.
2. Use a camera tripod to support the solar site evaluator if at all possible. The T nut will fit a camera tripod. Otherwise, use the handle.

3. At the specific place to be evaluated for solar access, set up the solar site evaluator and level it by means of the bull's-eye level.
4. Orient the tool so that the 0° azimuth reference line faces true south. Refer to Section H.1 for finding true south.
5. Bring your eye close to the top of the sight (cotton-swab tip), and look through the mask toward the south from the building site.
6. Evaluate the site by determining how much of the solar window is blocked.
7. If a record of the site is desired, draw on the acetate with a washable marker the outline of the objects viewed through the mask. By using clear acetate overlays, you can record any number of sites.

APPENDIX I

Heliodons

I.1 INTRODUCTION

Heliodons, which were described in Section 6.17, are powerful design tools for generating solar-responsive architecture. For economy, most heliodons use one light to simulate the sun. However, by using many lights, it is possible to create conceptually clear heliodons that are excellent teaching tools as well as good analysis tools. The type of heliodon chosen depends on the main purpose of the tool.

For schools of architecture, planning, and building, the author recommends one of two conceptually clear heliodons, of which the Sun Simulator is described in Section I.2 and the Sun Emulator in Section I.3. For low cost, compactness, and simplicity, the author recommends the tabletop heliodon described in Section I.4. That heliodon, however, is most appropriate for professionals who have a good understanding of solar geometry. Section I.5 describes how to make a bowling ball heliodon.



Figure I.2 The author helped the Faculty of Architecture at Chiang Mai University, Thailand, build this Sun Simulator Heliodon. It uses 50 W MR16 halogen lamps.

I.2 THE SUN SIMULATOR HELIODON

The Sun Simulator Heliodon is shown in Figures 6.19a and I.2. It has to be custom-built for a specific latitude, although it can be adjusted for a range of latitudes plus or minus 5° from the constructed latitude. It is ideal for learning solar geometry and for generating enthusiasm for solar design, because the device simulates our everyday experience. It is also extremely easy to use.

Although the Sun Simulator Heliodon can be built to any size, the author recommends a diameter of more than 10 ft (3 m), and larger is better. The author, who invented this heliodon, provides a complete set of computer-aided design drawings for free. Simply request an electronic copy by e-mail: lechnnm@auburn.edu.

I.3 THE SUN EMULATOR HELIODON

The Sun Emulator Heliodon shown in Figures 6.19b and I.3 was developed by the author for those situations where the Sun Simulator Heliodon was not practical. The Sun Emulator is completely assembled in the factory and shipped to the site ready to go. It can be moved from room to room and requires a footprint of only 3 × 6 ft (1 × 2 m). It can simulate all latitudes from the equator to the poles. However, because it is smaller than the Sun Simulator, smaller models must be used.

The Sun Emulator is made by High Precision Devices, located in Boulder, Colorado. They can be contacted at www.hpd-online.com. The author has given the invention away and derives no income from it.



Figure I.3 In its storage mode, the Sun Emulator table is rotated into the vertical position and the sun-path rings are placed at their 0° latitude position.

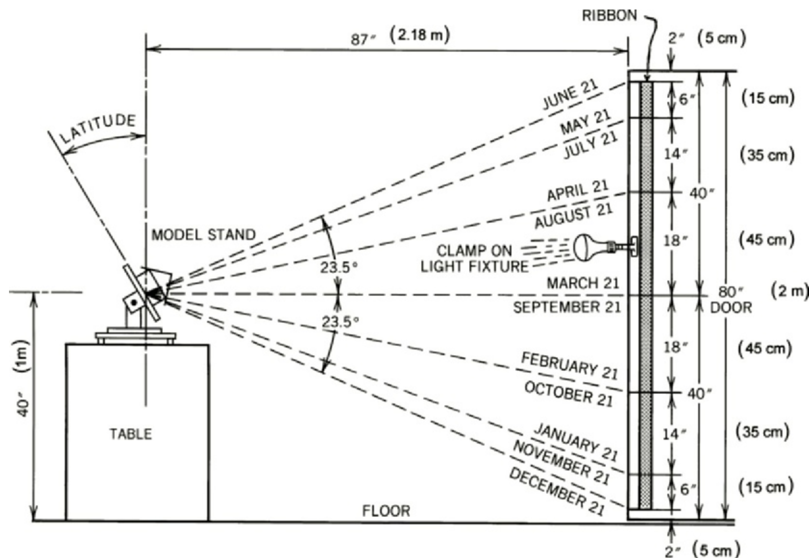


Figure I.4a These dimensions for the tabletop heliodon are critical.

I.4 THE TABLETOP HELIODON

The heliodon shown in Figures 6.17b and 6.18 consists of three parts:

1. A labeled ribbon, which is taped to the edge of a door
2. The clamp-on lighting fixture, which is supported by the edge of a door
3. The model stand, which rests on an ordinary table

Figure I.4a shows the precise spatial relationship of these three parts.

Ribbon

The cloth ribbon should be of a light color, about 2 in. (5 cm) wide and 76 in. (190 cm) long. The locations for the various months should be marked as indicated in Figure I.4a (e.g., the top end should be labeled as June 21).

Light

Use a 50 W light weight reflector lamp or a lower wattage LED lamp in a clamp-on lighting fixture. The goal is to get a good quantity of light to shine on the model stand so that shadows are easy to see.

Model Stand

Note that the heliodon model stand can be made to any size. The dimensions given here in the I-P system are for convenience only. Any size and thickness of material will work as long as the tilt table can tilt 90° from horizontal to vertical and rotate 360° about the base.

Parts List

- 2 pieces of ⅜ in. plywood 12 × 12 in.
- 1 piece of ⅜ in. plywood 12 × 10½ in.
- 2 pieces of wood ¾ × 1½ × 7 in. (Part A)
- 2 pieces of wood ¾ × 3½ × 7 in. (Part B)
- 3 carriage bolts ¼ in. diameter 2 in. long, with washers and winged nuts
- 6 wood screws 2 in. long, size #8
- 4 soft rubber no-slip feet (not gliders)
- 2 sheets of cardboard (not corrugated) about 8 × 8 in. to act as washers
- 1 nail to act as a pointer

Construction Procedure

Drill a ¼ in. diameter hole in the center of the fixed base, in the corresponding location in the rotating base, and in Parts A and B (Figs. I.4d and I.4e). Drill a ¾ in. hole in one part A as shown in Figure I.4e. Also, for the wood screws, drill 3⁄32 in. holes in the rotating base and the tilt table as indicated in Figure I.4d. Drill all holes as accurately as possible.

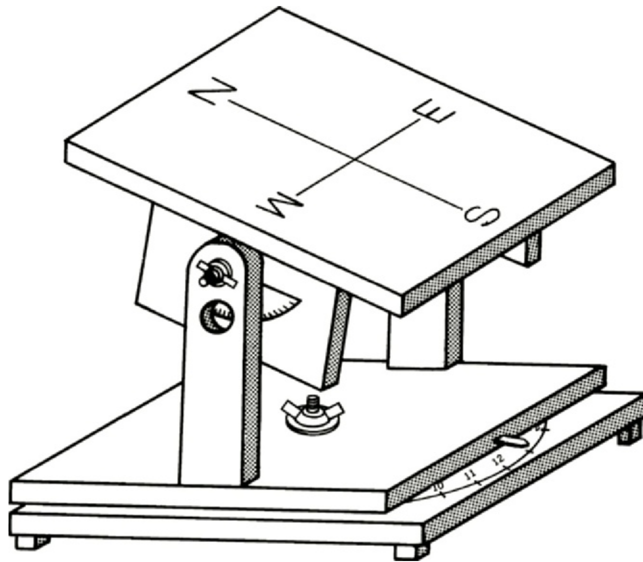


Figure I.4b Isometric view of the tabletop heliodon model stand.

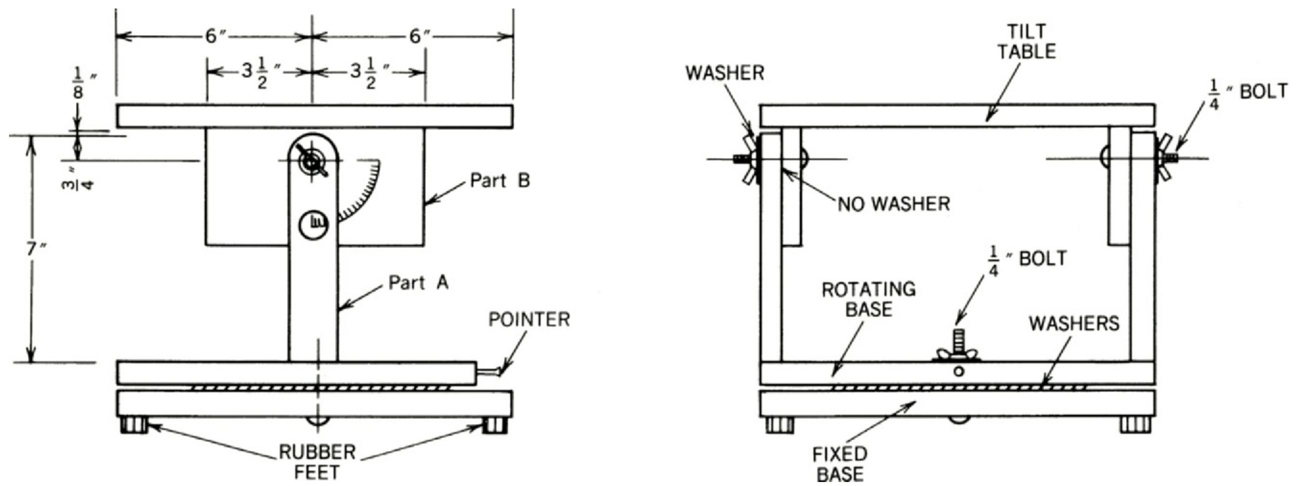


Figure I.4c West elevation (left); south elevation (right). When working in SI units, use dimensions that are convenient, because actual size does not matter.

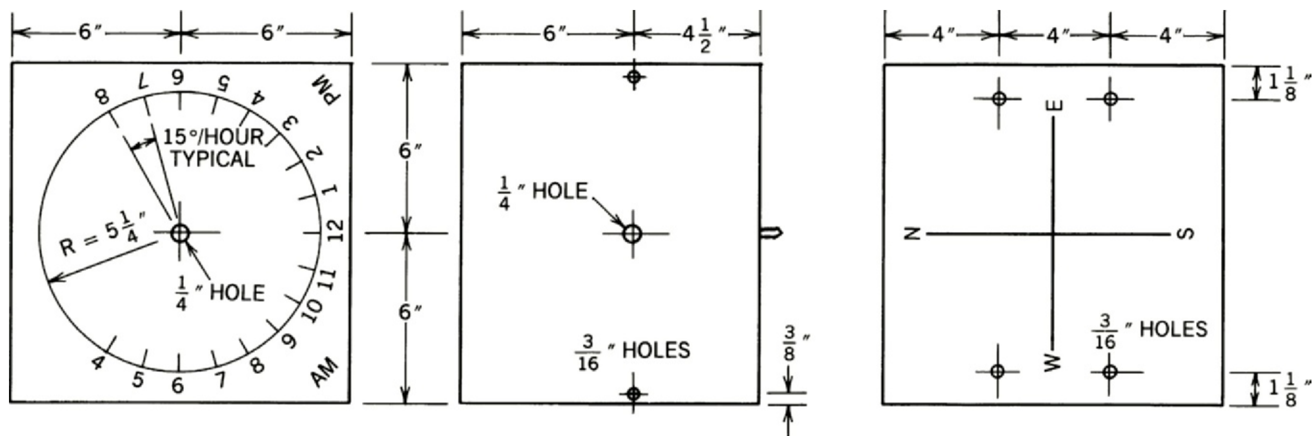


Figure I.4d Fixed base (left); rotating base (center); tilt table (right).

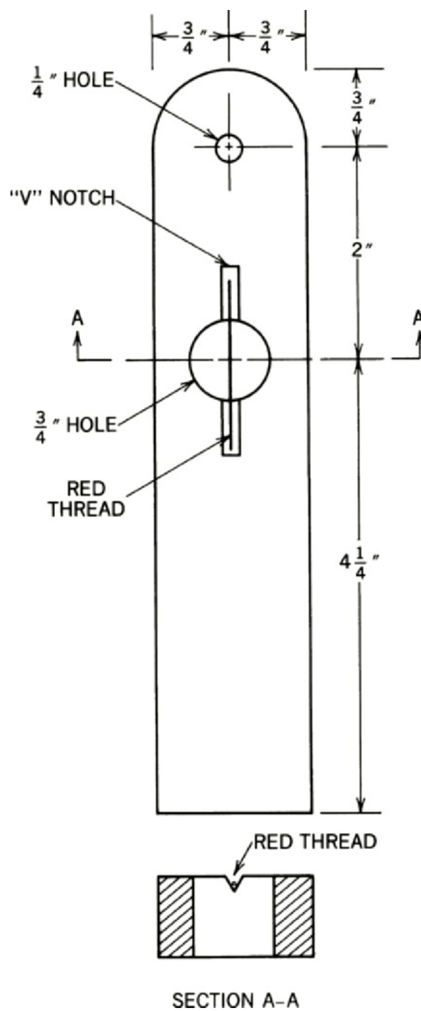


Figure I.4e Detail of part A for the west side

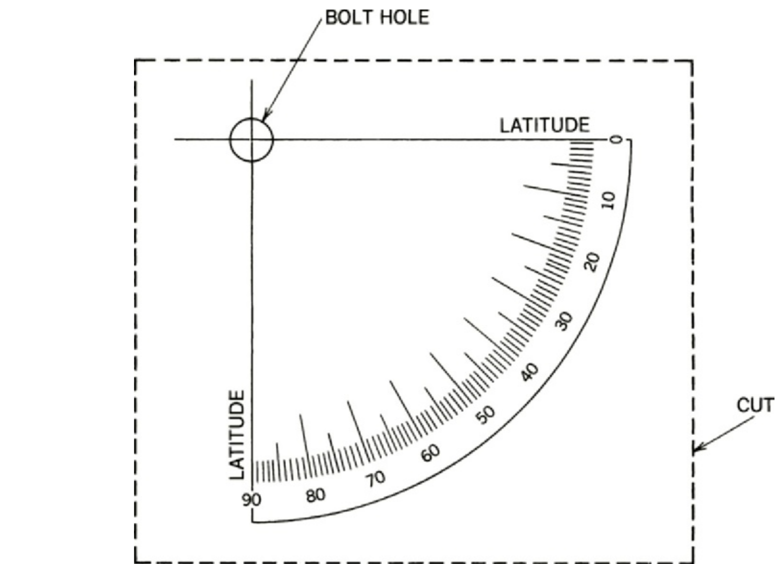


Figure I.4f Copy this sun machine latitude scale so that it has a radius of 2 1/4 inches.

Prepare both parts A by rounding one end of each. On the part A with the ¾ in. hole, cut a V groove as shown in Figure I.4e. Glue a red thread into this groove to form a reference line across the hole. Make sure that no glue or thread protrudes above the surface. Screw parts A to the rotating base as shown in Figure I.4c. Be sure to drill 3/32 in. pilot holes to prevent splitting of parts A and B. Part A with the ¾ in. hole should be on the west side and have the surface with the thread face inward.

Attach parts B to parts A with two carriage bolts. Then screw the tilt table to parts B as shown in Figure I.4c. Again drill 3/32 in. pilot holes first in parts B to prevent splitting of the wood. Photocopy Figure I.4f, cut along the dashed lines, and use a paper hole puncher to very carefully punch out the hole for the carriage bolt. Glue this latitude scale to the outside surface of part B on the west side. Make sure that the holes are aligned and that the zero line is parallel to the tilt table (Fig. I.4c, left). Cover the scale with several coats of varnish for protection.

On the fixed base, label the hours of the day, and on the tilt table, label the cardinal directions of the compass (Fig. I.4d). Attach the four soft rubber feet to the bottom of the fixed base. Use the nail to make a pointer on the rotating base (Fig. I.4d). From the cardboard, make two washers about 8 in. in diameter with a ¼ in. hole in the center. Assemble the tilt table with the cardboard washers between the rotating base and the fixed base. However, there should be no washers between parts A and B.

Make sure that the rotating base can move very freely on the fixed base. It should, however, be possible to completely lock in place the tilt table when the winged nuts on the east and west sides are tightened. Check to make sure that the pointer, 12 noon, and south are all aligned. Also check to make sure that the latitude reads 90° for a horizontal tilt table and 0° when the tilt table is vertical.

Directions for Initial Setup

1. Tape the ribbon to the edge of a door as shown in Fig. I.4a.
2. Make sure that the clamp-on light fixture has a sufficiently long extension cord so that it can be placed anywhere along the vertical edge of the door.
3. Place the model stand on a table so that the center of the tilt table is 87 in. (218 cm) from the door edge and about 40 in. (100 cm) above the floor. Also make sure that 12 noon on the model stand faces the light on the door.

Directions for Use

1. Set and fix latitude by adjusting the angle of the tilt table.
2. Attach the model to the tilt table with pushpins or clamps. Align south of the model with south of the tilt table.
3. Set the clamp-on light to the desired month and aim the lamp at the model.
4. Turn the rotating base to the desired hour of the day.



Figure I.4g The alternate mode of use for the model stand uses a sundial.

5. The model will now exhibit the desired sun penetration and shading.

Notes

1. Since the greatest accuracy occurs at the center of the tilt table, small models are more accurate than large models. However, many large models (e.g., site models) can be shifted around so that the part examined is always near the center of the tilt table.
2. The dynamics of sun motion can be easily simulated. Rotate the tilt table about its vertical axis to simulate the daily cycle. Move the light vertically along the edge of the door to simulate the annual cycle of the sun at any particular time.
3. A correctly constructed heliodon will illuminate the east side of a model during morning hours. Check that the tilt table indicates 0° latitude when it is in a vertical position. This would be the correct tilt for a model of a building located at the equator. Also make sure that the tilt table is horizontal when the latitude scale reads 90° (North Pole).

Alternate Mode of Use of the Heliodon

For greater accuracy, a source with more parallel light is required. Indoors, a slide projector at the far end of a corridor would give fairly parallel light rays. The best source of all, of course, is the sun. Since neither of these two sources of light can be moved up or down along the edge of a door, an alternate method of use for the model stand is required. Figure I.4g shows how a sundial is used in this alternate mode. Appendix E describes how sundials can easily be made for various latitudes.

Procedure for Alternate Mode of Use of the Heliodon

1. Attach the sundial of the appropriate latitude to the model in such a way that the base of the sundial is parallel to the floor plane of the model. Also align the south orientation of the model with that of the sundial.
2. Attach the model to the heliodon model stand. In this mode of use, the adjustments for latitude and time of day are ignored on the model stand.
3. Tilt and rotate the model stand until the gnomon of the sundial casts a shadow on the intersecting lines of the month and hour desired.
4. The model now exhibits with great accuracy the desired sun penetration and shadows (Fig. I.4g).

I.5 THE BOWLING BALL HELIODON

This bowling ball heliodon is simple to make and to use. However, it can only be used with sundials. It uses a bowling ball to allow easy adjustments in three axes, to simulate the sun angles for hours, months, and latitude (Fig. I.5). Because this heliodon can be readily disassembled, it is very portable and easily stored.

The heliodon base is made of two pieces of plywood that are approximately 20 × 30 in. (50 × 75 cm) and ¾ in. (2 cm) thick. Cut the plywood into the shapes shown in Figure I.5. The two pieces of plywood are then assembled into a cruciform shape. The top slits allow a pipe to be inserted. The top ring of this PVC pipe is then coated with rubber (e.g., plasti-dip) so that the tabletop mounted to the bowling ball can be set at a steep angle without slipping. The plywood tabletop is attached to the bowling ball with a 6 × ½ in. machine screw and a 2 in. (5 cm) collar made from the same PVC pipe that acts as a stand. Make sure that the screw head is countersunk so that the model has a flat surface to sit on. Used bowling balls are available at low cost at any bowling alley.

Caution: Users must be made aware of the danger of the bowling ball falling on their feet.

The Bowling Ball Heliodon was invented by Victor Olgyay, AIA, and Anna Maria R. Grune.

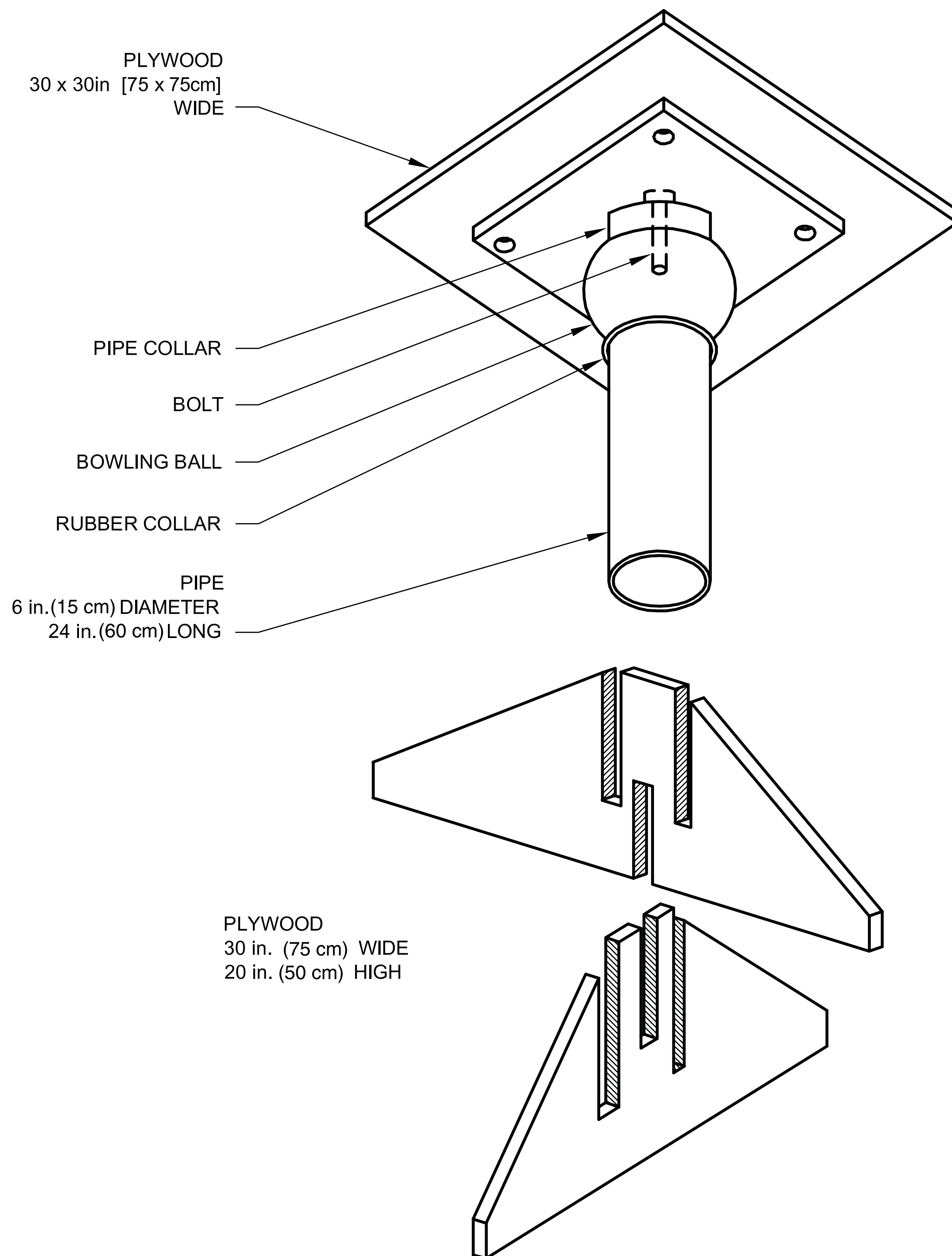


Figure I.5 An exploded view of the construction of a bowling ball heliodon is shown.

APPENDIX J

Tables of R-Values

These technical tables are provided because the thermal resistance of building materials is a key aspect of sustainability. Table J.1 provides the thermal resistance of most common building materials. Table J.2 shows how the thermal resistance of an air space varies with orientation, direction of heat flow, and/or the reflectance/emittance of the air space surface. Table J.3 shows the resistances of common doors. For the thermal resistance of windows, see Fig. 15.9a.

Table J.1 R-Values for Typical Building Materials

	I-P System						SI System					
					Heat Capacity						Heat Capacity	
Material	Thickness in Inches	R per Inch*	R for Thickness Listed†	Density (lb/ft^3)	By Weight (Btu/lb. °F)	By Volume (Btu/ft^3 °F)	Thickness in Meters	R per Meter‡	R for Thickness Listed§	Density (kg/m^3)	By Weight (J/kg °C)	By Volume (J/m^3 °C)
BRICK	4	0.1	0.5	120	0.19	22.8	0.1	0.7	0.09	1920	0.79	1525
CONCRETE BLOCKS												
Normal weight	4		0.7	69	0.22	15.18	0.1		0.13	1104	0.92	1015
	8		1.1	64	0.22	14.08	0.2		0.2	1024	0.92	942
	12		1.3	63	0.22	13.86	0.3		0.23	1008	0.92	927
Normal weight with insulated core	8		1.9	65	0.22	14.3	0.2		0.34	1040	0.92	9560
Lightweight with isulated core	8		5		0.21	0.21			0.9		0.88	1
STONE (lime or sand)	1	0.08		150	0.19	28.5	1	0.6		2400	0.79	1906
CONCRETE												
Normal weight	1	0.08		140	0.22	30.8	1	0.6		2240	0.92	2060
Lightweight	1	0.2→1.4					1	1.3→10				
WOOD												
Sheets of plywood, hardboard, particleboard, wood siding	1	1.2		34	0.29	9.86	1	8		544	1.21	659
Hardwoods	1	0.9		45	0.3	13.5	1	6		720	1.25	903
Softwoods	1	1.3		32	0.33	10.56	1	9		512	1.38	706
INSULATION												
Blankets												
Fiberglass	1	3.5					1	24				
Mineral wool	1	3.3					1	23				
Cotton fiber	1	3.9					1	27				
Loose fill												
Fiberglass	1	3					1	21				
Mineral wool	1	3.8					1	27				
Cellulosic fiber	1	3.5			0.33	0.33	1	25		16	1.38	22
Vermiculite–exfoliated	1	2.1		7	0.32	2.24	1	15		112	1.34	150
Perlite-expanded	1	2.7			0.26	0.26	1	19		16	1.09	17
Sawdust	1	2.2			0.33	0.33	1	14		16	1.38	22
Rigid boards												
Phenolic foam boad	1	8					1	56				
Polyurethane/ polyisocyanurate	1	6.5					1	46				
Polystyrene (extruded)	1	5					1	35				
Polystyrene (expanded-based board)	1	4					1	28				
Cellular glass	1	3		8.5	0.24	2.04	1	21		136	1	136

Glass fiber	1	4		9.5	0.23	2.185	1	28		152	0.96	146
Cork board	1	3.6					1	25				
Fiberboard	1	2.6					1	18				
Sprayed or Blown												
Polyurethane	1	6					1	48				
Cellulose	1	3.3										
Glass fiber	1	3.7										
Air-Krete	1	3.9		2.2				27				
Icynene	1	3.6		0.5				25				
Roofing												
Built-up roofing	0.38		0.3	70	0.35	24.5	0.0095		0.05	1120	1.46	1639
Asphalt shingles			0.4	70	0.3	21			0.07	1120	1.25	1404
Slate	0.5		0.1	201	0.3	60.3	0.0127		0.02	3216	1.25	4033
Wood shingles			0.9	40	0.31	12.4			0.16	640	1.3	829
Sheet metal			neg						neg			
GLASS	1		0.1						0.02			
GYPSUM OR PLASTER BOARD	0.38		0.3	50	0.26	13	0.009		0.05	800	1.09	869
	0.5		0.5	50	0.26	13	0.013		0.09	800	1.09	869
	0.62		0.6	50	0.26	13	0.016		0.1	800	1.09	869
FINISH FLOORING OR CEILING												
Hardwood	0.75		0.7	45		45	0.019		0.13	720	4.18	3010
Tile-asphalt, rubber, vinyl	0.13		neg	120	0.3	36	0.0032		neg	1920	1.25	2408
Tile-linoleum, ceramic, terrazzo	0.13		0.1	80	0.3	24	0.0032		0.02	1280	1.25	1605
Tile-cork	0.13	2.2	0.3	25	0.48	12	0.0032	15.4	0.05	400	2.01	803
Carpet	1	2.1	1					15	0.18			
Lay-in ceiling tile	0.5	2.5	1.3	18	0.14	2.52	0.0127	18	0.23	288	0.59	169
STRAW BALES	1	1.5→2.5						10→21				
EARTH												
Dry, loose	1	0.3						2.1				
Damp, packed	1	0.1						0.7				
METALS		neg						neg				
SAND	1	0.5		95	0.2	19		3.5		1520	0.84	1271
SNOW	1	0.2						1.4				

*°F · ft^2 · h/Btu · in.
†°F · ft^2 · h/Btu.
‡°C · m^2/W.
§°C · m^2/W.

Table J.2 R-Values of Air Spaces

	Surface or Space	Direction of Heat Flow	Reflective Quality of Surfaces† Nonreflective* I-P‡	Nonreflective* SI§	Bright Aluminimum Foil† I-P‡	Bright Aluminimum Foil† SI§
Surface Air Films						
Still air	Horizontal	Up	0.6	0.10	1.3	0.22
	Vertical	Horizontal	0.7	0.12	1.7	0.29
	Horizontal	Down	0.9	0.15	4.6	0.78
Moving air (any position)			0.1–0.3	0.02–0.05		
Air Spaces						
	Horizontal	Up	0.8	0.14	2.2	0.37
	Vertical	Horizontal	0.9	0.15	3.2	0.54
	Horizontal	Down				
	¾ in. air space		1	0.17	3.4	0.58
	3½ ft air space		1.1	0.19	8.7	1.48

*Any surface other than polished metal.
†Any polished metal–radiant barrier.
‡°F · ft^2 · h/Btu.
§°C · m^2/W.

Table J.3 Thermal Resistance for Slab Doors

Doors	I-P R*	I-P U†	SI R‡	SI U§
Wood (solid)	2	0.5	0.36	2.8
w/storm door	3.3	0.3	0.59	1.7
Steel	1.6–5	0.2–0.6	0.29–0.89	3.4–1.12

*Total thermal resistance (°F · ft^2 · h/Btu)
†U-coefficient (Btu/°F · ft^2 · h).
‡total thermal resistance (°C · m^2/W).
§U-coefficient (W/°C · m^2).

APPENDIX K

Resources

K.1 BOOKS

The following books are highly recommended. Because they cover the whole range of environmental-control topics, they are listed here. (See the Bibliography for full citations. The list includes valuable and out-of-print books.)

Anderson, B., ed. *Solar Building Architecture*.

Barnett, D. L., with W. D. Browning. *A Primer on Sustainable Building*.

Brown, G. Z., and M. DeKay. *Sun, Wind, and Light: Architectural Design Strategies*, 3rd ed.

Cofaigh, E. O., J. E. Olley, and J. O. Lewis. *The Climatic Dwelling: An Introduction to Climatic-Responsible Residential Architecture*.

Daniels, K. *The Technology of Ecological Building: Basic Principles and Measures, Examples and Ideas*.

Flynn, J. E., A. Stegal, G. T. Steffy, and G. R. Steffy. *Architectural Interior Systems*.

Givoni, B. *Climate Considerations in Building and Urban Design*.

Goulding, J. R., J. O. Lewis, and T. C. Steemers, eds. *Energy Conscious Design: A Primer for Architects*.

Grondzik, W., and A. G. Kwok. *Mechanical and Electrical Equipment for Buildings*, 12th ed.

Lstiburek, J. W. *Builder's Guide—Hot-Dry and Mixed-Dry Climates; Builder's Guide—Cold Climates; Builder's Guide—Mixed Climates*.

Moore, F. *Environmental Control Systems*

Olgay, V. *Design with Climate: A Bioclimatic Approach to Architectural Regionalism*.

Pearson, D. *The Natural House Catalog: Everything You Need to Create an Environmentally Friendly Home*.

Thomas, R., ed. *Environmental Design: An Introduction for Architects and Engineers*.

Tuluca, A. *Energy-Efficient Design and Construction for Commercial Buildings*.

Watson, D., and K. Labs. *Climatic Design: Energy-Efficient Building Principles and Practices*.

K.2 JOURNALS

Eco-Structure: Improving Environmental Performances of Buildings and Their Surroundings. www.eco-structure.com

Environmental Building News. 122 Birge Street, Suite 30, Brattleboro, VT 05301. 802-257-7300. www.buildinggreen.com

Environmental Design and Construction. 299 Market Street, Suite 320, Saddle Brook, NJ 07663-5312. 415-863-2614. www.edcmag.com

Home Energy: The Magazine of Residential Energy Conservation. 2124 Kittredge Street, No. 95, Berkeley, CA 94704-9942. 510-524-5405.

Home Power: The Hands-on Journal of Home-made Power. Ashland, OR: Home Power, Inc. P.O. Box 5520, Ashland, OR 97520. 916-475-3179.

Renewable Energy World. James & James Ltd. 35-37 William Road, London, NW1 3ER U.K. 144 171 387 8558; fax: 144 387 8998. E-mail: rew@jxj.com. www.jxj.com

Solar Today. The journal of the American Solar Energy Society. 2400 Central Avenue, Unit G-1, Boulder, CO 80301. 303-443-3130. E-mail: ases@ases.org. www.solartoday.org

K.3 VIDEOS

Affluenza. Host, Scott Simon. Produced by KCTS/Seattle and Oregon Public Broadcasting (OPB). KCTS Television, 1997. Approximately 57 minutes. 1-800-937-5387. Discusses the environmental impact of a high standard of living.

An Inconvenient Truth. www.takepart.com/an-inconvenient-truth/film

Arithmetic, Population, and Energy. Dr. Albert A. Barlett. 1994. 65 minutes. University of Colorado, ITS-Media Services, Campus Box 379, Boulder, CO 80309-0379. 303-492-1857, fax: 303-492-7017. E-mail: Kathleen.Albers@colorado.edu

Keeping the Earth: Religious and Scientific perspectives on the Environment. 1996. 27 minutes. Publications Department, Union of Concerned Scientists, Two Brattle Square, Cambridge,

MA 02238-9105. 617-547-5552. www.ucsusa.org

Kilowatt Ours. www.kilowattours.org

World Population, Produced by Population Connection, 1400 16th Street NW, Suite 320, Washington, DC 20036. 1-800-POP-1956. www.popconnect.org

K.4 ORGANIZATIONS

American Institute of Architects, Committee on the Environment. www.aia.org/cote

American Society of Heating, Refrigeration, and Air-Conditioning Engineers (ASHRAE). www.ashrae.org. Works to educate members of the field and to set standards for the industry.

American Society of Landscape Architects (ASLA). www.asla.org. A professional organization that, among other activities, provides training and advocates for livable communities and the environment.

American Solar Energy Society. www.ases.org. A nonprofit organization advocating the use of solar and other renewable energy sources, including through work with professionals.

American Wind Energy Association. www.awea.org. Advocates for and educates on the use of wind power.

Architecture 2030. www.architecture2030.org. A U.S.-based, non traditional and flexible environmental advocacy group focused on protecting the global environment by using innovation and common sense to develop, and quickly implement, bold solutions to global warming. One of its activities was the creation of the 2030 Palette (see below).

Building Science Consulting. www.buildingscience.com. A Boston-based firm involved in building design, construction, and operation. It focuses on sustainable building in promoting energy efficiency and environmental protection.

California Lighting Technology Center. www.cltc.ucdavis.edu

Center for Biological Diversity. www.EndangeredSpeciesCondoms.com. The only environmental group that clearly states the connection between the state of the environment and human population.

Energy and Environmental Building Association. www.eeba.org. Provides information to transform the residential design, development, and construction industries.

Florida Solar Energy Center. www.fsec.ucf.edu. The state's primary research facility on solar energy and other advanced fuels.

GeoExchange/Geothermal Heat Pump Consortium. www.geoexchange.org. Provides geother mal heat pumps in houses.

IESNA Illuminating Engineering Society. www.iesna.org. Pub lishes information on the latest knowledge in lighting.

International Association of Lighting Designers (IALD). www.iald.org. Sets standards for lighting design and refers customers to lighting designers.

International Solar Energy Society. www.ises.org. Promotes and educates about solar energy and all other areas of renewable energy.

Lighting Design Lab. www.lightingdesignlab.com. Promotes quality lighting and sustainable lighting systems. A good source of information on lighting.

Lighting Resource Center. www.lrc.rpi.edu. A reliable source of objective information about lighting technologies, applications, and products. As part of Rensselaer Polytechnic Institute, it offers master's and Ph.D. programs in lighting. It provides training to people in the building professions.

National Association of Home-builders Research Center (NAHBRC). www.nahbrc.org. A resource for reliable, objective information and research on housing-construction and development issues. Has published green building standards.

National Institute of Building Science, Building Enclosure Technology and Environmental Council. www.nibs.org/betec.

National Resources Defense Council. www.nrdc.org. The nation's most effective environmental action organization.

Negative Population Growth, Inc. (NPG). www.npg.org. Provides information on the environmental impact of population growth.

North American Sundial Society. www.sundials.org. Dedicated to the study, development, history, and preservation of sundials.

North Carolina Solar Center. www.ncsc.ncsu.edu. Clearinghouse for solar and other renewable energy for citizens of North Carolina and beyond.

Northeast Sustainable Energy Association (NESEA). www.nesea.org. The Northeast's leading organization of professionals and concerned citizens working in the areas of sustainable energy and whole systems thinking.

Oak Ridge National Laboratory. www.ornl.gov. Originally created to produce plutonium for the Manhattan Project, it is now a leading researcher in environmental and energy technologies.

Pacific Energy Center. www.pge.com/pec. Offers educational programs, design tools, advice, and support to create energy-efficient buildings and comfortable indoor environments.

Population Connection. www.populationconnection.org. Explores issues involving connections between sustainability and population.

Rocky Mountain Institute. www.rmi.org. Founded by Hunter

and Amory Lovins, the RMI is a source of information for sustainability in most areas.

Southface. www.southface.org. A nonprofit organization providing educational and outreach programs for both architects and the general public.

Sustainable Buildings Industry Council (SBIC). www.nibs.org/?page=sbic. Promotes green building using a whole-building approach.

Union of Concerned Scientists. www.ucsusa.org. The leading science-based nonprofit organization working for a healthy environment and a safer world.

U.S. Environmental Protection Agency. www.epa.gov. The U.S. government's main regulatory agency for environmental matters.

U.S. Green Building Council. www.usgbc.org. Administers the LEED program, which certifies buildings as green.

Worldwatch Institute. www.worldwatch.org. Reports on sustainability issues worldwide.

K.5 WEB-BASED RESOURCES

2030 Palette. www.2030palette.org. A free interactive online platform that puts the principles and actions behind low-carbon and resilient-built environments at the fingertips of architects, planners, and designers worldwide.

Green Building Advisor. www.greenbuildingadvisor.com. The complete source for building, design, and remodeling green homes.

APPENDIX L

Conversion Factors between the Inch-Pound (I-P) System and the International System of Units (SI)

The International System of Units (SI) is the modern version of the metric system. All major countries except the United States have switched to the SI system. When England switched to the SI system, it no longer made sense to call our system the English system. Thus, we now call it the Inch-Pound (I-P) System of units. To speed up the switch to the SI system, the U.S. federal government requires all construction documents for federal buildings to be drawn in SI units.

SI PREFIXES
tera (T) = 1 trillion
giga (G) = 1 billion
mega (M) = 1 million
kilo (k) = 1,000
hecto (h) = 100
deka (da) = 10
deci (d) = 0.1
centi (c) = 0.01
milli (m) = 0.001
micro (μ) = 1 millionth
nano (n) = 1 billionth
pico (p) = 1 trillionth

To convert	To	Multiply by
Length		
inches (in.)	centimeters	2.54
inches	millimeters	25.4
feet (ft)	meters	0.305
yards (yd)	meters	0.914
miles (mi)	kilometers	1.61
centimeters (cm)	inches	0.394
meters (m)	feet	3.28

(Continued)

To convert	To	Multiply by
meters	yards	1.09
kilometers (km)	feet	3,280
kilometers	miles	0.621
Area		
square inches	square centimeters	6.45
square feet	square meters	0.0929
acres	hectares	0.405
square miles	square kilometers	2.59
square centimeters	square inches	0.155
square meters	square feet	10.8
hectares (ha)	acres	2.47
square kilometers	square miles	0.386
acres	square yards	4,840
acres	square feet	43,560
hectares	square meters	10,000
Energy (work, heat, power)		
British thermal unit (Btu)	kilowatt-hours	0.000293
therms	British thermal unit	100,000
resistance per inch	resistance per meter	6.93
resistance (I-P) actual thickness	resistance [SI] actual thickness	0.174
U-coefficient (I-P)	U-coefficient [SI]	5.73
Btu (energy)	kilocarlories	0.252
Btu (energy)	kilojoules	1.06
Btu/h (power)	watts	0.293
Btu/h ft^2 (energy transfer)	watts per square meter	3.16
Btu/°F (heat capacity)	kilojoules per kelvin	1.9
Btu/lb°F (specific heat)	kilojoules per kilogram per kelvin	4.18
Btu/h°F ft (thermal conductivity)	watts per kelvin per meter	1.73
Btu/h°F ft^2 (conductance)	watts per kelvin per square meter	5.67
watts	Btu per hour	3.41
watts per square meter	Btu per square foot	0.317
kilocalories	Btu	3.97
kilocalories	joules	4190
kilojoules	Btu	0.948
kilojoules per kilogram	Btu per pound	0.43
kilowatt-hours	megajoules	3.6
megajoules	kilowatt-hours	0.278
US horsepower (hp)	watts	746
horsepower	kilowatts	0.746
kilowatts	horsepower	1.34

To convert	To	Multiply by
Light		
footcandle	lux	10.8
Volume		
cubic inches	cubic centimeters	16.4
cubic feet	cubic meters	0.0283
cubic feet	gallons	7.48
cubic feet	liters	28.3
cubic yards	cubic meters	0.765
cubic centimeters	cubic inches	0.061
cubic meters	cubic feet	35.3
cubic meters	cubic yards	1.3
liters	cubic feet	0.0353
Liquids		
US gallons	liters	3.79
US gallons water	pounds water	8.35
liters	fluid ounces (US)	33.8
liters	quarts	4.23
liters	gallons (US)	0.264
quarts	liters	0.946
barrels	US gallons	42
Weight		
ounces (oz)	grams	28.3
pounds (lb)	kilograms	0.454
pounds	grams	454
grams (g)	ounces	0.0353
kilograms (kg)	pounds	2.2
Density		
pounds per cubic foot	kilograms per cubic meter	16
Speed		
feet per second (fps)	meters per second (mps)	0.305
meters per second	feet per minute	197
meters per second	miles per hour	2.24
miles per hour	kilometers per hour	1.61
miles per hour	meters per second	0.447
Temperature		
Celsius (°C)	Fahrenheit (°F)	multiply by 9, divide by 5, add 32
Fahrenheit (°F)	Celsius (°C)	subtract 32, multiply by 5, divide by 9
Celsius	Kelvin (K)	add 273.15

BIBLIOGRAPHY

Abrams, Donald W. *Low-Energy Cooling*. New York: Van Nostrand Reinhold, 1986.

AIA Research Corporation. *Regional Guidelines for Building Passive Energy Conserving Homes*. Washington, DC: U.S. Government Printing Office, 1980.

———. *Solar Dwelling Design Concepts*. Washington, DC: U.S. Government Printing Office, 1976.

Akbari, Hashem, J. S. Huang, and S. Davis. *Cooling Our Communities: A Guidebook on Tree Planting and Light-Colored Surfacing*. Washington, DC: EPA and DOE/Lawrence Berkeley Laboratory [LBL-31587], 1992.

Allard, Francis, ed. *Natural Ventilation in Buildings: A Design Handbook*. London: James & James, 1998.

Allen, Edward, drawings by David Swoboda and Edward Allen. *How Buildings Work: The Natural Order of Architecture*, 2nd ed. New York: Oxford University Press, 1995.

Allen, Edward, and Joseph Iano. *The Architect's Studio Companion: Technical Guidelines for Preliminary Design*, 4rd ed. New York: John Wiley & Sons, 2011.

American Wind Energy Association. *Permitting Small Wind Turbines: A Handbook*. Available at www.awea.org/smallwind/documents/permitting.pdf.

Ander, Gregg D. *Daylighting Performance and Design*, 2nd ed. Hoboken, NJ: John Wiley & Sons, 2003.

Anderson, Bruce. *Solar Energy: Fundamentals in Building Design*. New York: McGraw-Hill, 1977.

———, ed. *Solar Building Architecture*. Cambridge, MA: MIT Press, 1990.

Anderson, Bruce, and Malcolm Wells. *Passive Solar Energy*. Amherst, NH: Brick House Publishing, 1994.

Andrews, F. T. *Building Mechanical Systems*. New York: McGraw-Hill, 1977.

ASHRAE. *Air-Conditioning Systems Design Manual*. Atlanta: ASHRAE, 1993.

———. *ASHRAE Greenguide: The Design, Construction, and Operation of Sustainable Buildings*. Atlanta: ASHRAE, 2013.

———. *ASHRAE Handbook: Fundamentals*. Atlanta: ASHRAE, 2013.

———. *ASHRAE Terminology of Heating, Ventilation, Air Conditioning, and Refrigeration*, 2nd ed. Atlanta: ASHRAE, 1991.

———. *Passive Solar Heating Analysis: A Design Manual*. Atlanta: ASHRAE, 1984.

Bachmann, Leonard. *Integrated Buildings: The Systems Basis of Architecture*. Hoboken, NJ: John Wiley & Sons, 2003.

Baird, George. *The Architectural Expression of Environmental Control Systems*. New York: Spon, 2001.

Baker, Nick, and Koen Steemers. *Daylight Design of Buildings*. London: James & James, 2002.

Balcomb, J. Douglas. *Passive Solar Buildings*. Cambridge, MA: MIT Press, 1992.

Balcomb, J. Douglas, and Robert W. Jones. *Workbook for Workshop on Advanced Passive Solar Design*, July 12, 1987, Portland, Oregon. Santa Fe, NM: Balcomb Solar Association, 1987.

Banham, Reyner. *The Architecture of the Well-Tempered Environment*, 2nd ed. London: Architectural Press, 1984.

Barnett, Dianna Lopez, and William D. Browning. *A Primer on Sustainable Building*. Snowmass, CO: Rocky Mountain Institute, 1995.

Barreneche, R. A. "High Heat, High Tech." *Architecture*, October 1995, pp. 107–113.

Bartlett, Albert A. "Forgotten Fundamentals of the Energy Crisis."*American Journal of Physics* 46 (9), September 1978.

Bearg, David W. *Indoor Air Quality and HVAC Systems*. Boca Raton, FL: Lewis Publishers/CRC Press, 1993.

Bell, James, and William Burt. *Designing Buildings for Daylight*. London: Construction Research Communications, 1995.

Bennett, Robert. *Sun Angles for Design*. Bala Cynwyd, PA: Robert Bennett, 1978.

Bobenhausen, William. *Simplified Design of HVAC Systems*. New York: John Wiley & Sons, 1994.

Boonstra, Chiel, ed. *Solar Energy in Building Renovation*. London: James & James, 1997.

Boutet, Terry S. *Controlling Air Movement: A Manual for Architects and Builders*. New York: McGraw-Hill, 1987.

Bowen, Arthur, Eugene Clark, and Kenneth Labs, eds. *Proceedings of the International Passive and Hybrid Cooling Conference*, Miami Beach, FL, Nov. 6–16, 1981. Newark, DE: American Section of the International Solar Energy Society, 1981.

Bowen, Arthur, and S. Gingras. "*Wind Environments in Buildings and Urban Areas*." Paper presented at the Sunbelt Conference, December 1978.

Boyce, Peter. *Human Factors in Lighting*, 2nd ed. New York: Macmillan, 2003.

Boyce, P. R., N. H. Eklund, and S. N. Simpson. "Individual Lighting Control: Task Performance, Mood and Illuminance," *Journal of Illuminating Engineering Society* 29: 131–142.

Boyer, Lester, and Walter Grondzik. *Earth Shelter Technology*. College Station, TX: Texas A&M University 1987.

Bradshaw, Vaughn. *Building Control Systems*, 3rd ed. New York: John Wiley & Sons, 2006.

———. *The Building Environment: Active and Passive Control Systems*, 3rd ed. Hoboken, NJ: Wiley, 2006.

Brown, G. Z., and Mark DeKay. *Sun, Wind, and Light: Architectural Design*

Strategies, 3rd ed. New York: John Wiley & Sons, 2014.

Brown, Robert D., and Terry J. Gillespie. *Microclimatic Landscape Design: Creating Thermal Comfort and Energy Efficiency*. New York: John Wiley & Sons, 1995.

Buckley, Shawn. *Sun Up to Sun Down*. New York: McGraw-Hill, 1979.

Butti, Ken, and John Perein. *A Golden Thread: 2500 Years of Solar Architecture*. New York: Van Nostrand Reinhold, 1980.

Campbell, C. J. *The Coming Oil Crisis*. Multi-Science Publishing Company & Petroconsultants S.A., 1988.

Campbell, C. J., and Jean H. Leherrére. "The End of Cheap Oil." *Scientific American* 278 (3). March 1998.

Carmody, John. *Builder's Foundation Handbook*. Oak Ridge National Laboratory, 1991. www.ornl.gov/sci/roofs+walls/foundation/ORNL_CON-295.pdf

Carmody, John, Stephen Selkowitz, and Lisa Herschong. *Residential Windows: A Guide to New Technologies and Energy Performance*, 3rd ed. New York: Norton, 2007.

Carmody, John, S. Selkowitz, E. S. Lee, D. Arasten, and T. Willmert, *Window Systems for High-Performance Buildings*. New York, Norton, 2004.

Carmody, John, and Raymond Sterling. *Earth Sheltered Housing Design*, 2nd ed. New York: Van Nostrand Reinhold, 1985.

Carver, Norman F., Jr. *Italian Hilltowns*. Kalamazoo, MI: Documan Press, 1993.

Clegg, Peter, and Derry Watkins. *Sunspaces: New Vistas for Living and Growing*. Charlotte, VT: Garden Way Publishing, Storey Communications, 1987.

Climate Atlas of the United States. Asheville, NC: U.S. Department of Commerce Environmental Science Services Administration, Environmental Data Service, 1983.

Climate Change: State of Knowledge. Washington, DC: Office of Science and Technology Policy, 1997.

Cofaigh, Eoin O., John A. Olley, and J. Owen Lewis. *The Climatic Dwelling: An Introduction to Climatic-Responsive Residential Architecture*. London: James & James, 1996.

Commission of the European Communities Directorate–General XII for Science Research and Development. *Daylighting in Architecture: A European Reference Book*, N. Baker, A. Fanchiotti, and K. Steemers, eds. London: James & James, 1993.

Commoner, Barry. *The Politics of Energy*. New York: Knopf, 1979.

Comparative Climatic Data for the United States/. . ./Prepared at the National Climatic Center. Asheville, NC: U.S. Department of Commerce, National Oceanic and Atmospheric Administration.

Cook, Jeffrey, ed. *Award Winning Passive Solar/House Designs*. New York: McGraw-Hill, 1984.

———. "*Cooling as the Absence of Heat: Strategies for the Prevention of Thermal Gain*," *Proceedings of the International Passive and Hybrid Cooling Conference*, Miami Beach, FL, Nov, 6–16, 1981, eds. Arthur Bowen et al. Newark, DE: American Section of the International Solar Energy Society, 1981.

———, ed. *Passive Cooling*. Cambridge, MA: MIT Press, 1989.

Cooling Our Communities: A Guidebook on Tree Planting and Light Colored Surfacing. Washington, DC: U.S. Environmental Protection Agency, Office of Policy Analysis, Climate Change Division, 1992.

Cooling with Ventilation (SERI/SP-273-2966; DE96010701). Golden, CO: Solar Energy Research Institute, 1986.

Crosbie, Michael J. *Green Architecture: A Guide to Sustainable Design*. Rockport, MA: Rockport Publications, 1994 Distributed by North Light Books, Cincinnati, OH.

Crowther, Richard L., ed. *Ecologic Architecture*. Butterworth Architecture, 1992.

Curtis, W. "Desert Illumination." *Architecture*, October 1995, pp. 56–65.

Cuttle, Christopher. *Lighting by Design*. Burlington, MA: Architectural Press, 2003.

Dagostino, Frank R. *Mechanical and Electrical Systems in Construction and Architecture*. Englewood Cliffs, NJ: Prentice Hall,2009.

Daniels, Klaus. *The Technology of Ecological Building: Basic Principles and Measures, Examples and Ideas*. Trans. by Elizabeth Schwaiger. Basel, Switzerland: Birkhäuser, 1997.

Davidson, Joel. *The New Solar Electric Home: The Photovoltaics How-To Handbook*. Ann Arbor, MI: Aatec Publications, 1987.

Davies, Colin, and Ian Lambot. *Commerzbank Frankfurt: Prototype for an Ecological High-Rise*. Surrey, UIT Watermark, 1997.

DiLaura, David. *A History of Light and Lighting*. New York: Illuminating Engineering Society of North America, 2005.

Druse, Ken, with Margaret Roach. *The Natural Habitat Garden*. New York: Clarkson Potter, 1994.

Duly, Colin. *The Houses of Mankind*. New York: Thames and Hudson, 1979.

Dunnett, Nigel, and Noël Kingsbury. *Planting Green Roofs and Living Walls*. Portland, OR: Timber Press, 2008.

Earth Pledge. *Green Roofs: Ecological Design and Construction*. Atglen, PA: Schiffer, 2005.

Easton, David. *The Rammed Earth House*. White River Junction, VT: Chelsea Green Publishing, 1996.

Egan, M. David. *Concepts in Thermal Comfort*. Englewood Cliffs. NJ: Prentice-Hall, 1975.

Egan, M. David, and Victor W. Olgay. *Architectural Lighting*, 2nd ed. Boston: McGraw-Hill, 2001.

Ehrlich, Paul R., and Anne H. Ehrlich. *The Population Explosion*. New York: Simon & Schuster Touchtone Books, 1991.

Energy Design Resources. *Skylighting Guidelines*. www.energydesign-resources.com/.

Environmental Protection Agency. *Cooling Our Communities*. Washington, DC: U.S. Environmental Protection Agency, Office of Policy Analysis, Climate Change Division, 1992.

Evans, Benjamin E. *Daylight in Architecture*. New York: McGraw-Hill, 1981.

Fathy, Hassan. *Natural Energy and Vernacular Architecture: Principles and Examples with Reference to Hot*

Arid Climates. Chicago: University of Chicago Press, 1986.

Fitch, James Marston. *American Building: 1. The Historical Forces That Shaped It*, 2nd ed. New York: Schocken, 1973.

———. *The Architecture of the American People*. New York: Oxford University Press, 2000.

———, ed. *Shelter: Models of Native Ingenuity: A Collection of Essays Published in Conjunction with an Exhibition of Katonah Gallery March 13–May 23, 1982*. The Katonah Galley, 1982.

Fitch, James M., with William Bobenhausen. *American Building: 2. The Environmental Forces That Shape It*. New York: Schocken, 1999.

Flynn, John E., J. A. Kremers, A. W. Segil, and G. Steffy. *Architectural Interior Systems: Lighting, Acoustics, Air Conditioning*, 3rd ed. New York: Van Nostrand Reinhold, 1992.

Fontoynont, Marc. *Daylighting Performance of Buildings*. London: James & James, 1999.

Ford, Robert M. *Mississippi Houses: Yesterday Toward Tomorrow*. Mississippi State University, 1982.

Foster, Ruth S. *Homeowner's Guide to Landscaping That Saves Energy Dollars*. New York: David McKay, 1978.

Francis, Mark. *Village Homes: A Community by Design: Case Studies in Land and Community Design*. Landscape Architecture Foundation, 2003.

Franta, Gregory, Kristine Anstead, and Gregg D. Ander. *Glazing Design Handbook for Energy Efficiency*. American Institute of Architects, 1997.

Futagawa, Yukio, ed. and photography. *Light and Space: Modern Architecture*. Tokyo: A.D.A. EDITA Tokyo Co., 1994.

Gelbspan, Ross. *The Heat Is On: The High Stakes Battle Over Earth's Threatened Climate*. Reading, MA: Addison-Wesley, 1997.

Gipe, Paul. *Wind Energy Comes of Age*. New York: John Wiley & Sons, 1995.

———. *Wind Power for Home and Business: Renewable Energy for the 1990's and Beyond*. Post Mills, VT: Chelsea Green, 1993.

Givoni, Baruch. *Climate Considerations in Building and Urban Design*. New York: Van Nostrand Reinhold, 1998.

———. "Integrated-Passive Systems for Heating of Buildings by Solar Energy," *Architectural Science Review* 24 (2): 29–41.

———. *Man, Climate and Architecture*, 2nd ed. New York: Van Nostrand Reinhold, 1976.

———. *Passive and Low Energy Cooling of Buildings*. New York: Van Nostrand Reinhold, 1994.

Golany, Gideon. *Design and Thermal Performance: Below-Ground Dwellings in China*. Newark, DE: University of Delaware Press; London: Associated University Press, 1990.

———, ed. *Housing in Arid Lands—Design and Planning*, New York: John Wiley & Sons, 1980.

Gordon, Gary, and James L. Nuckolls. *Interior Lighting for Designers*, 4th ed. Hoboken, NJ: John Wiley & Sons, 2003.

Gore, Al. *Earth in the Balance: Ecology and the Human Spirit*. New York: Houghton Mifflin, 1992.

Goulding, John R., J. Owen Lewis, and Theo C. Steemers, eds. *Energy Conscious Design: A Primer for Architects*. London: Batsford, 1992.

Grondzik, Walter, and Alison G. Kwok. *Mechanical and Electrical Equipment for Buildings*, 12th ed. Hoboken, NJ: John Wiley & Sons, 2014.

Groesbeck, Wesley, and Jan Stiefel. *The Resource Guide to Sustainable Landscapes and Gardens*, 2nd ed. Environmental Resources, 1995.

Grosslight, Jane. *Lighting Kitchens and Baths*. Tallahassee, FL: Durwood, 1993.

———. *Light, Light, Light: Effective Use of Daylight and Electric Lighting in Residential and Commercial Spaces*. Tallahassee, FL: Durwood, 1998.

Guiding Principles of Sustainable Design. Denver, CO: U.S. Department of the Interior, National Parks Service, Denver Center, 1993.

Guise, David. *Design and Technology in Architecture*, rev. ed. New York: Van Nostrand Reinhold, 1991.

Guzowski, Mary. *Daylighting for Sustainable Design*. New York: McGraw-Hill, 1999.

———. *Towards Zero Energy Architecture: New Solar Design*. London: Laurence King Publishing, 2012.

Hawken, Paul. *The Ecology of Commerce*. New York: HarperCollins,2010.

Hawken, Paul, Amory Lovins, and L. Hunter Lovins. *Natural Capitalism: Creating the Next Industrial Revolution*. Boston: Little, Brown, 2010.

Heinz, Thomas A. "Frank Lloyd Wright's Jacobs II House," *Fine Home Building*, June/July 1981.

Helms, Ronald N., and M. Clay Belcher. *Lighting for Energy-Efficient Luminous Environments*. New York: Prentice Hall, 1991.

Heschong, Lisa. *Thermal Delight in Architecture*. Cambridge, MA: MIT Press, 1979.

Hestnes, Anne Grete, Robert Hastings, and Bjarne Saxhof. *Solar Energy House: Strategies, Technologies, Examples*. London: James & James, 1997.

Highshoe, Gary L. *Native Trees, Shrubs, and Vines for Urban and Rural America: A Planting Design Manual for Environmental Designers*. New York: Van Nostrand Reinhold, 1988.

Hopkinson, R. G. *Architectural Physics: Lighting*. London: H. M. Stationery Office, 1963.

Hopkinson, Ralph Galbraith, P. Petherbridge, and James Longmore. *Daylighting*. London: Heinemann, 1966.

Hottes, Alfred C. *Climbers and Ground Covers, Including a Vast Array of Hardy and Subtropical Vines Which Climb or Creep*. New York: De La Mare, 1947.

Houben, Hugo, and Hubert Guillaud. *Earth Construction: A Comprehensive Guide*. London: Intermediate Technology Publications, 1994.

Humm, O. *[Photovoltaik und Architekture] Photovoltaics in Architecture: The Integration of Photovoltaic Cells in Building Envelopes*. Basel and Boston: Birkhaüser, 1993

Hyde, Richard. *Climate Responsive Design: A Study of Buildings in Moderate and Hot Humid Climates*. London: Spon, 2000.

The IESNA Lighting Handbook: Reference and Application. 10th ed. New York:

Illuminating Engineering Society of North America, 2014.

International Energy Agency. *Passive Solar Commercial and Institutional Buildings: A Sourcebook of Examples and Design Insights*. S. R. Hastings, ed. New York: John Wiley & Sons, 1994.

Jaffe, Martin S., and Duncan Erley, illustrated by Dava Lurie. *Protecting Solar Access for Residential Development: A Guidebook for Planning Officials*. Washington, DC: U.S. Department of Housing and Urban Development, Office of Policy Development and Research, 1979.

Janis, Richard R, and William K. Y. Tao. *Mechanical and Electrical Systems in Buildings*, 5th ed. Englewood Cliffs, NJ: Prentice Hall, 2013

Jones, David Lloyd. *Architecture and the Environment: Bioclimatic Building Design*. Woodstock, NY: Overlook Press/Peter Mayer, 1998.

Jones, R. W., and R. D. McFarland. *The Sunspace Primer: A Guide to Passive Solar Heating*. New York: Van Nostrand Reinhold, 1984.

Kachadorian, James. *The Passive Solar House: Using Solar Design to Heat and Cool Your Home*. White River Junction, VT: Chelsea Green Publishing, 1997.

Karlen, Mark, and James Benya. *Lighting Design Basics*. Hoboken, NJ: John Wiley & Sons, 2004.

K. Cathcart Anders Architects. *Building Integrated Photovoltaics*. National Renewable Energy Laboratory, 1993. Available from NTIS, NTIS Order No. DE95004056.

Kellert, Stephen R., and Edward O. Wilson. *The Biophilia Hypothesis*. Washington, DC: Island Press, 1993.

King, Bruce. *Buildings of Earth and Straw: Structural Design for Rammed Earth and Straw-Bale Architecture*. Sausalito, CA: Ecological Design Press, 1996.

Knight, Paul A. *Mechanical Systems Retrofit Manual: A Guide for Residential Design*. New York: Van Nostrand Reinhold, 1987.

Knowles, Ralph L. *Energy and Form: An Ecological Approach to Urban Growth*. Cambridge, MA: MIT Press, 1974.

———."On Being the Right Size"; "The Ritual of Space"; "Rhythm and Ritual"; "The Solar Envelope." www.rcf.usc.edu/~rknowles.

———. *Ritual House: Drawing on Nature's Rhythms for Architecture and Urban Design*. Washington, D.C.: Island Press, 2006.

———. *Rituals of Place*. Retrieved March 3, 2008, from www.rcf.usc.edu/~rknowles/rituals_place/rituals_place.html

———. *Sun Rhythm Form*. Cambridge, MA: MIT Press, 1981.

Kohlmaier, Georg, and Barna von Sartory. *Das Glashaus: Ein Bautypus des 19. Jahrhunderts*. Munich: Prestel-Verlag, 1981.

Komp, Richard J. *Practical Photovoltaics — Electricity from Solar Cells*, 3rd ed. Ann Arbor, MI: Aatec, 1995.

Konya, Allan. *Design Primer for Hot Climates*. London: Architectural Press; New York: Whitney Library of Design, 1980.

Köster, Helmut. *Dynamic Daylighting Architecture Basics, Systems, Projects*. Basel: Birkhäuser, 2004.

Krigger, John. *Residential Energy: Cost Savings and Comfort for Existing Buildings*. Helena, MT: Saturn Resources Management, 1994.

Kukreja, C. P. *Tropical Architecture*. New Delhi: Tata McGraw-Hill, 1978.

Kwok, Alison G., and Walter T. Grondzik. *The Green Studio Handbook: Environmental Strategies for Schematic Design*. Burlington, MA: Oxford, 2011.

Lam, William M. C. *Perception and Lighting as Formgivers for Architecture*. Christopher Hugh Ripman, ed. New York: Van Nostrand Reinhold, 1992.

———. *Sunlighting as Formgiver for Architecture*. New York: Van Nostrand Reinhold, 1986.

Lang, Paul V. *Principles of Air Conditioning*, 5th ed. Albany, NY: Delmar, 1995.

Leibowitz, Sandra. *Ecological Design and Building Schools*. New Village Press, 2005.

Leslie, Russell P., and Kathryn M. Conway. *The Lighting Pattern Book for Homes*. New York: McGraw-Hill, 1996.

Leslie, Russell P., and Paula A. Rodgers. *The Outdoor Lighting Pattern Book*. New York: McGraw-Hill, 1996.

Lewis, Jack. *Support Systems for Buildings*. Englewood Cliffs, NJ: Prentice Hall, 1986.

Littlefair, P. J. *Designing Innovative Daylighting*. Watford, Hertfordshire, England: Construction Research Communications, 1996.

Los Alamos National Laboratory. *Passive Solar Heating Analysis—A Design Manual*. Atlanta: ASHRAE, 1984.

———. "More Profit with Less Carbon." *Scientific American*, September 2005, 74–82.

———. *Reinventing Fire: Bold Business Solutions for the New Energy Era*. White River Junction, VT: Chelsea Green Publishing, 2011.

———. *Soft Energy Paths*. New York: Harper Colophon Books, 1977.

———. *Winning the Oil Endgame*. Snowmass, CO: Rocky Mountain Institute, 2004. Available at www.oilendgame.com.

Lovins, Amory B., and L. Hunter Lovins. *Brittle Power: Energy Strategy for National Security*. Andover, MA: Brick House Publishing, 1982.

Lstiburek, Joseph W. *Builder's Guide to Cold Climates: Details for Design and Construction*. Newtown, CT: Taunton Press, 2000.

———. *Builder's Guide to Hot-Dry and Mixed-Dry Climates: A Systems Approach to Designing and Building Homes That Are Healthy, Comfortable, Durable, Energy Efficient and Environmentally Responsible*. Building Science Corporation, 1998.

———. *Builder's Guide to Mixed Climates: Details for Design and Construction*. Newtown, CT: Taunton Press, 2000.

———. *Exemplary Home Builder's Field Guide*. Triangle Park, NC: North Carolina Alternative Energy Corporation, 1994.

Lstiburek, Joseph W., and John Carmody. *Moisture Control Handbook*. New York: Van Nostrand Reinhold, 1993.

Lyle, David. *The Book of Masonry Stoves: Rediscovering an Old Way of Warming*. White River Junction, VT: Chelsea Green Publishing, 1984.

Lyle, John Tillman. *Design for Human Ecosystems: Landscape, Land Use, and Natural Resources*. Washington, DC: Island Press, 1999.

———. *Regenerative Design for Sustainable Development*. New York: John Wiley & Sons, 1994.

Mann, Peter A. *Illustrated Residential and Commercial Construction*. Englewood Cliffs, NJ: Prentice Hall, 1989.

Matus, Vladimir. *Design for Northern Climates: Cold-Climate Planning and Environmental Design*. New York: Van Nostrand Reinhold, 1988.

Mazria, Edward. *The Passive Solar Energy Book: Expanded Professional Ed*. Emmaus, PA: Rodale Press, 1979.

McDonough, William, and Michael Braungart. "The Next Industrial Revolution." *Atlantic Monthly*, October 1998. Retrieved March 3, 2008, from www.theatlantic.com/doc/199810/environment

McHarg, Ian L. *Design with Nature*. New York: John Wiley & Sons, 1995.

McIntyre, Maureen, ed. *Solar Energy: Today's Technologies for a Sustainable Future*. Boulder, CO: ASES, 1997.

McPherson, E. Gregory, ed. *Energy Conserving Site Design*. Waldorf, MD: American Society of Landscape Architects, 1984.

Miller, Burke. *Buildings for a Sustainable America: Case Studies*. Boulder, CO: ASES, 1997.

Millet, Marietta S. *Light Revealing Architecture*. New York: Van Nostrand Reinhold, 1996.

Moffat, Anne Simon, and Marc Schiler. *Energy-Efficient and Environmental Landscaping*. South Newfane, VT: Appropriate Solutions Press, 1993.

———. *Landscape Design That Saves Energy*. New York: Morrow, 1981.

Moore, Fuller. *Concepts and Practice of Architectural Daylighting*. New York: Van Nostrand, 1985.

———. *Environmental Control Systems*. New York: McGraw-Hill, 1993.

Nabokov, Peter, and Robert Easton. *Native American Architecture*. New York: Oxford University Press, 1989.

National Audubon Society and Croxton Collaborative, Architects. *Audubon House. Building the Environmentally Responsible, Energy-Efficient Office*. New York: John Wiley & Sons, 1994.

Neumann, Dietrich. *Architecture of the Night: The Illuminated Building*. Munich: Prestel, 2002.

Norton, John. *Building with Earth: A Handbook*. London: Intermediate Technology Publications, 1996.

Norwood, Ken, and Kathleen Smith. *Rebuilding Community in America: Housing for Ecological Living, Personal Empowerment, and the New Extended Family*. Berkeley, CA: Shared Living Resource Center, 1995.

Nuckolls, James L. *Interior Lighting*, 2nd ed. New York: John Wiley & Sons, 1983.

NY-Star Builder's Field Guide. Albany, NY: NY-Star, 1994.

Olgyay, Aladar, and Victor Olgyay. *Solar Control and Shading Devices*. Princeton, NJ: Princeton University Press, 1957.

Olgyay, Victor. *Design with Climate: A Bioclimatic Approach to Architectural Regionalism*. Princeton, NJ: Princeton University Press, 1953.

Olivieri, Joseph B. *How to Design Heating-Cooling Comfort Systems*, 4th ed. Troy, MI: Business News Publisher, 1987.

Ottesen, Carole. *The Native Plant Primer: Trees, Shrubs, and Wildflowers for Natural Gardens*. New York: Crown, 1995.

Panchyk, Katherine. *Solar Interior: Energy Efficient Spaces Designed for Comfort*. New York: Van Nostrand Reinhold, 1991.

Pearson, David. *The Natural House Catalog: Everything You Need to Create an Environmentally Friendly Home*. New York: Fireside, 1996.

———. *The New Natural House Book: Creating a Healthy, Harmonious, and Ecologically Sound Home*, 2nd ed. New York: Simon & Schuster, 1998.

Pepchinski, Mary. "Commerzbank." *Architectural Record*, January 1998.

Perlin, John. *From Space to Earth: The Story of Solar Electricity*. Ann Arbor, MI: Aatec, 1999.

Perlin, John, and Amory Lovins. *Let It Shine: The 6,000-Year Story of Solar Energy*. New World Library, 2013.

Petit, Jack, Debra L. Bassert, and Cheryl Kollin. *Building Greener Neighborhoods: Trees as Part of the Plan*, 2nd ed. Washington, DC: American Forests: Home Builders Press, 1998.

Phillips, Derek. *Daylighting: Natural Light in Architecture*. Amsterdam: Elsevier, 2004.

———. *Lighting Modern Buildings*. Oxford: Architectural Press, 2000. *Photovoltaics in the Building Environment*. American Institute of Architects, 1996.

Potts, Michael. *The New Independent Home: People and Houses That Harvest the Sun*. Rev. ed. White River Junction, VT: Chelsea Green Publishing, 1999.

Ramsey/Sleeper Architectural Graphic Standards, 11th ed. John R. Hoke, ed. New York: John Wiley & Sons, 2007.

Rapoport, Amos. *House Form and Culture* (Foundations of Cultural Geography Series). Englewood Cliffs, NJ: Prentice Hall, 1969.

Recommendations to the United Nations Commission on Sustainable Development: Final Report on the NGO Renewable Energy Initiative. Freiburg, Germany: ISES, 1995.

Reid, Esmond. *Understanding Buildings: A Multidisciplinary Approach*. Cambridge, MA: MIT Press, 1984.

Reif, D. K. *Solar Retrofit: Adding Solar to Your Home*. Amherst, NH: Brick House, 1981.

Roaf, Sue, David Chrichton, and Fergus Nicol. *Adapting Buildings and Cities for Climate Change: A 21st-Century Survival Guide*. Oxford, UK: Architectural Press, 2005.

Roaf, Sue, and Fergus Nicol. *Adaptive Thermal Comfort: Principles and Practice*. New York: Routledge, 2012.

Robbins, Claude. *Daylighting: Design and Analysis*. New York: Van Nostrand Reinhold, 1986.

———, ed. *Energy Efficient Site Design*. New York: Van Nostrand Reinhold, 1983.

Robinette, Gary O., and Charles McClenon. *Landscape Planning for Energy Conservation*. New York: Van Nostrand Reinhold, 1983.

Rocky Mountain Institute Staff. *Green Development: Integrating Ecology and Real Estate*. New York: John Wiley & Sons, 1998.

Rudofsky, Bernard. *Architecture without Architects: A Short Introduction to Non-Pedigreed Architecture*. New York: Museum of Modern Art; Garden City, NJ: Doubleday, 1965.

———. *The Prodigious Builders: Notes Toward a Natural History of Architecture*. London: Secker and Warburg, 1997.

Ruffner, James A., and Frank E. Bair. *The Weather Almanac*, 2nd ed. Detroit, MI: Gale Research, 1997.

Rush, Richard D., ed. *The Building Systems Integration Handbook*. New York: John Wiley & Sons, 1986.

Santamouris, Mat, and D. Asimakopoulos, eds. *Passive Cooling of Buildings*. London: James & James, 1996.

Schaeffer, J. *A Place in the Sun: The Evolution of the Real Goods Solar Living Center*. White River Junction, VT: Chelsea Green,1997.

Scheer, Hermann. *A Solar Manifesto: The Need for a Total Energy Supply—and How to Provide It*. London: James & James, 1994.

Schiler, Marc. *Simplified Design of Building Lighting*. New York: John Wiley & Sons, 1997.

———, ed. *Simulating Daylight with Architectural Models*. Los Angeles: University of Southern California Press, 1985.

Sick, Friedrich, and Thomas Erge, eds. *Photovoltaics in Buildings: A Design Handbook for Architects*. London: James & James, 1996.

Singh, Madanjeet. *The Timeless Energy of the Sun for Life and Peace with Nature*. San Francisco: Sierra Club Books, 1998.

Solar Age. Published by Solar Age Inc., 1976–86; continued as *Progressive Builder*, published by International Solar Energy Society, 1986–87.

Solar Today. American Solar Energy Society. Monthly.

Steffy, Gary R. *Architectural Lighting Design*, 2nd ed. New York: John Wiley & Sons, 2001.

———. *Time-Saver Standards for Architectural Lighting*. New York: McGraw-Hill, 2000.

Stein, Benjamin, John S. Reynolds, W. T. Grondzik, and A. G. Kwok. *Mechanical and Electrical Equipment for Buildings*, 10th ed. New York: John Wiley & Sons, 2006.

Stein, Richard G. *Architecture and Energy: Conserving Energy Through Rational Design*. New York: Anchor Books, 1977.

Sternberg, Guy, and Jim Wilson. *Landscaping with Native Trees*. Shelburne, VT: Chapters Publishers, 1995.

Steven Winter Associates. *The Passive Solar Design and Construction Handbook*. Ed. Michael J. Crosbie. New York: John Wiley & Sons, 1998.

Strong, Steven J. *The Solar Electric House: Energy for the Environmentally Responsive, Energy-Independent Home*. White River Junction, VT: Chelsea Green, 1993.

Strong, Steven J., and William G. Scheller. *The Solar Electric House: A Design Manual for Home-Scale Photovoltaic Power Systems*. Emmaus, PA: Rodale Press, 1987.

Susanka, Sarah. *The Not So Big House: A Blueprint for the Way We Really Live*. Newtown, CT: Taunton Press, 1998.

Szokolay, Steven V. *Environmental Science Handbook for Architects and Builders*. New York: John Wiley & Sons, 1980.

———. *Introduction to Architectural Science: The Basis of Sustainable Design*. Oxford: Elsevier, 2004.

Tabb, Phillip. *Solar Energy Planning: A Guide to Residential Settlement*. New York: McGraw-Hill, 1984.

Taylor, John S. *Commonsense Architecture: A Cross-Cultural Survey of Practical Design Principles*. New York: Norton, 1983.

Thomas, Randall, ed. *Environmental Design: An Introduction for Architects and Engineers*. New York: Spon, 1999.

Traister, John E. *Residential Heating, Ventilating, and Air Conditioning: Design and Application*. Englewood Cliffs, NJ: Prentice Hall, 1990.

Trost, J. *Electrical and Lighting*. Upper Saddle River, NJ: Prentice Hall, 1999.

———. *Heating, Ventilating, and Air Conditioning*. Upper Saddle River, NJ: Prentice Hall, 1999.

Tuluca, Adrian. *Energy-Efficient Design and Construction for Commercial Buildings*. New York: McGraw-Hill, 1997.

Underground Space Center, University of Minnesota. *Earth Sheltered Housing Design: Guidelines, Examples, and References*. New York: Van Nostrand Reinhold, 1979.

U.S. Department of Energy, Office of Project and Facilities Management. *Site Development Planning for Energy Management*. 1985 DOE/MA-0129.

U.S. Department of Housing and Urban Development. *Moisture-Resistant Homes: A Best Practice Guide and Plan Review Tool for Builders and Designers with a Supplemental Guide for Homeowners*. www.huduser.org.

———. *Protecting Solar Access for Residential Development*. 1979. By Jaffe, M., and D. Erley HVD-PDR-445.

Van der Ryn, Sim. *The Toilet Papers: Recycling Waste and Conserving Water*. Ecological Design Press, 1995.

Van der Ryn, Sim, and Peter Calthorpe. *Sustainable Communities: A New Design Synthesis for Cities, Suburbs, and Towns*. San Francisco: Sierra Club Books, 1986.

Van der Ryn, Sim, and Stuart Cowan. *Ecological Design*. Washington, DC: Island Press, 1995.

Vickery, Robert L. *Sharing Architecture*. Charlottesville: University Press of Virginia, 1983.

Watson, Donald. *Designing and Building a Solar House: Your Place in the Sun*. Rev. ed. Charlotte, VT: Garden Way Publishing, 1977.

Watson, Donald, and Kenneth Labs. *Climatic Design: Energy-Efficient Building Principles and Practices*. New York: McGraw-Hill, 1993.

Wendehack, Clifford C. *Golf and Country Clubs*. New York: William Helburn, 1929.

Wilson, Edward O. *Biophilia*. Cambridge, MA: Harvard University Press, 1986.

———. "Is Humanity Suicidal: We're Flirting with the Extinction of Our Species." *New York Times Magazine*, May 30, 1993.

Wirtz, Richard. *HVAC/R Terminology: a Quick Reference Guide*. Upper Saddle River, NJ: Prentice Hall, 1998.

World Commission on Environment and Development. *Our Common Future*. Oxford: Oxford University Press, 1987.

Wright, Lawrence. *Home Fires Burning: The History of Domestic Heating and Cooking*. London: Routledge & Kegan Paul, 1964.

Zeiher, Laura C. *The Ecology of Architecture: A Complete Guide to Creating the Environmentally Conscious Building*. New York: Whitney Library of Design, 1996.

Zweibel, K. *Harnessing Solar Power: The Photovoltaics Challenge*. New York: Plenum Press, 1990.

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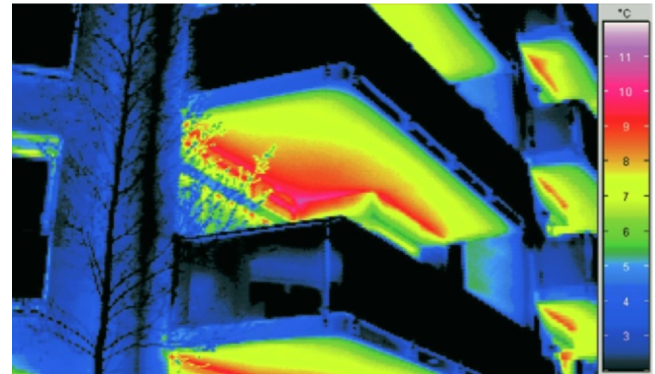
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COLOR PLATES



Colorplate 1 Exposed concrete floor slabs can be attractive when treated with an acid stain. They can provide valuable thermal mass, and they avoid the cost and potential air pollution from the use of additional floor coverings such as carpets.

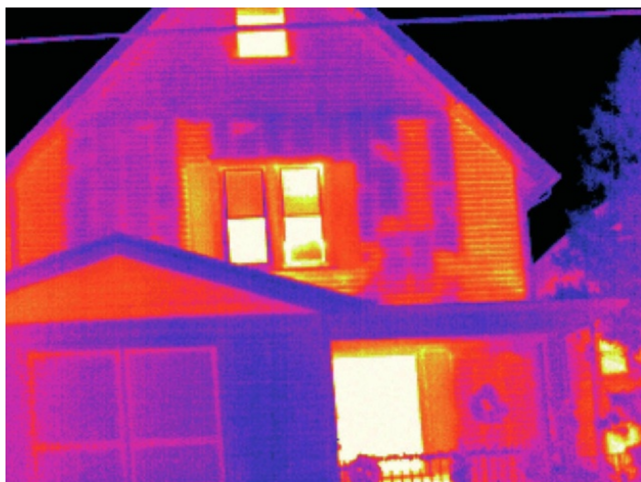


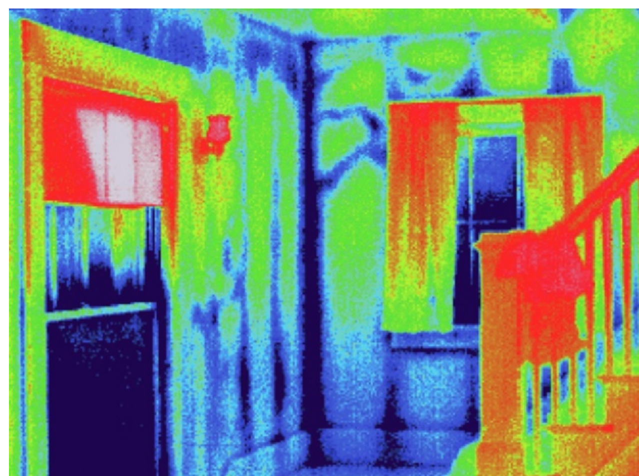
Colorplate 2 As the main causes of heat gain/loss are eliminated, heat bridges become an increasingly important problem. A concrete slab penetrating the thermal envelope is a major heat bridge, as documented in this thermogram of a balcony. (Image courtesy of Schöck USA Inc.)



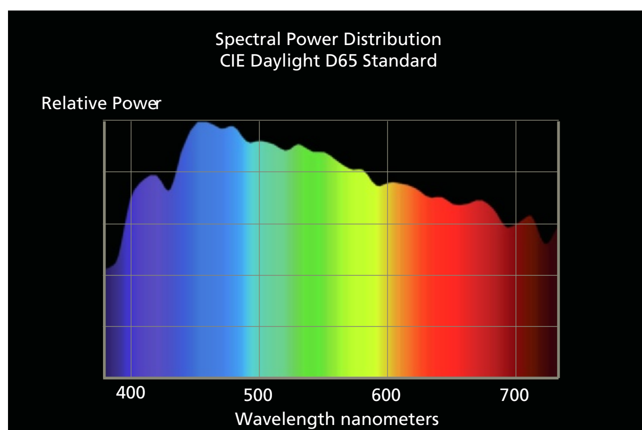


Colorplates 3 and 4 Two images of the same room show how still air stratifies. Colorplate 3 is taken with light, and Colorplate 4 is a thermogram taken with a long-wave infrared radiation "camera." (The lighter the color, the hotter the surface.) (Image courtesy of Stockton Infrared)

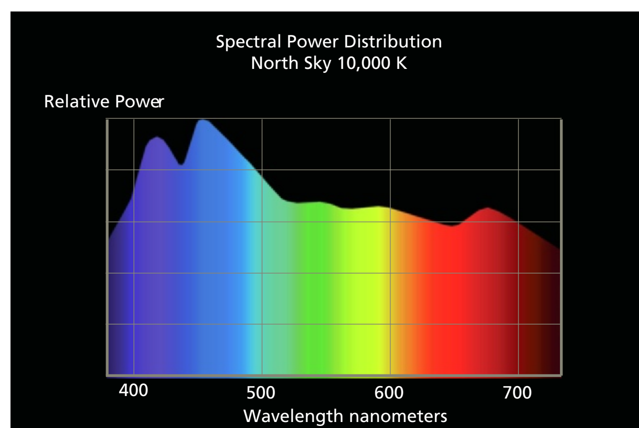




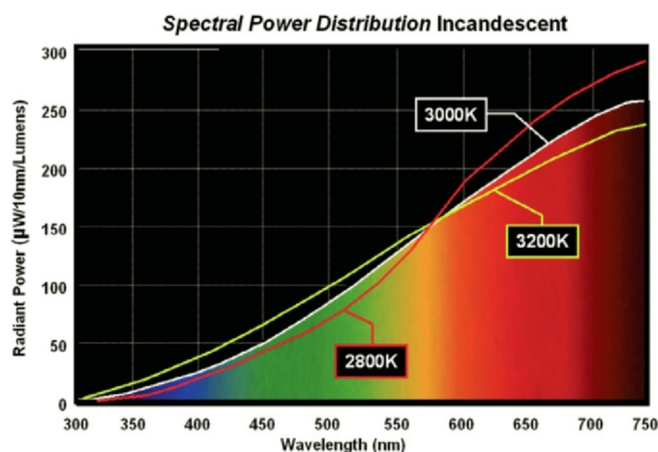
Colorplates 5 and 6 These two thermograms show weak areas in the thermal envelope. Colors are used to represent temperatures. Blue is the lowest (coldest) and white is the highest (hottest) temperature. In the outdoor photo (Colorplate 5), the windows are hottest, because they lose the most heat. Orange indicates wall areas with little or no insulation. In the indoor photo (Colorplate 6), the windows are now blue, because they are the coldest surface. (Copyright Shell Infrared)



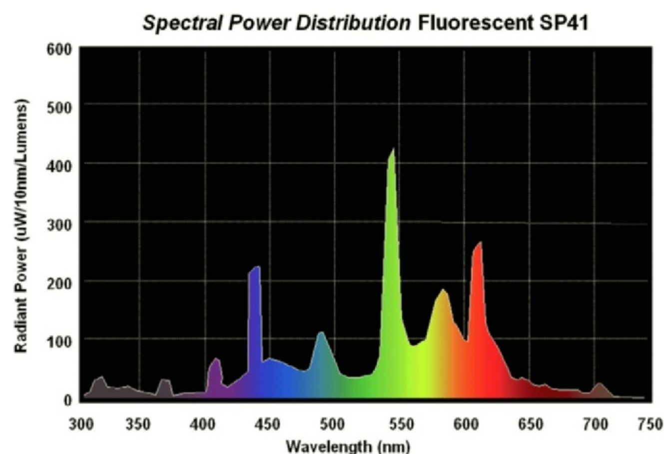
Colorplate 7 Standard daylight at noon, which includes sunlight, consists of almost equal amounts of all colors. It is an ideal light source. (Image courtesy of General Electric Company)



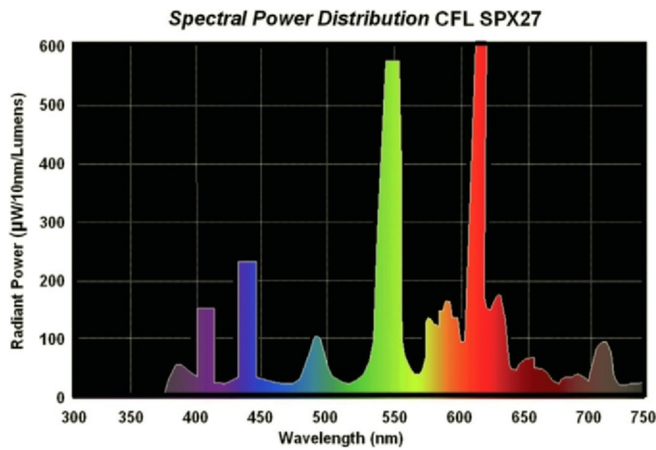
Colorplate 8 The light from the north sky is cool because of the large amount of blue light coming from the blue sky. (Image courtesy of General Electric Company)



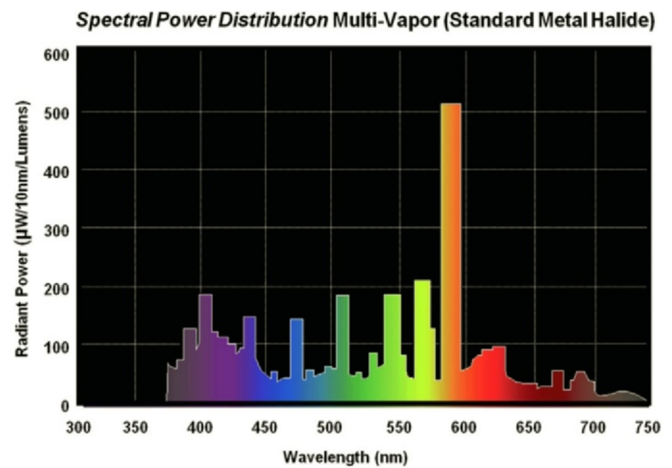
Colorplate 9 Incandescent lamps (2800K) produce very warm light because of the preponderance of light at the red end of the spectrum. Color rendition is high, because all colors are present. Halogen lamps (3200K) have a whiter light, because there is less red and more blue light. Halogen lamps are often used where high color rendition is required. (Image courtesy of General Electric Company)



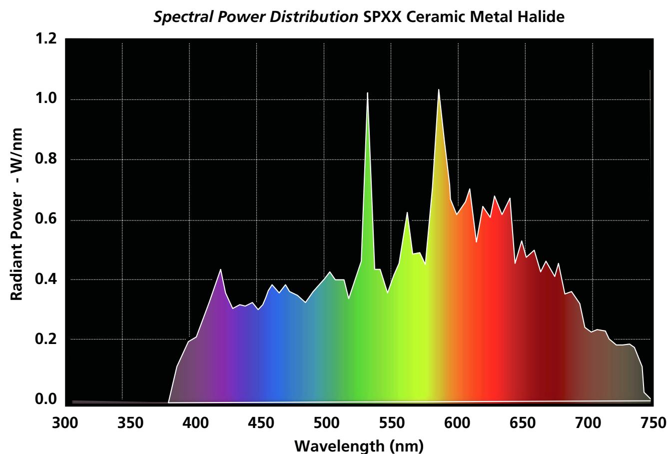
Colorplate 10 Because discharge lamps use ionization rather than incandescence, they produce much of their light at specific wavelengths. However, because of the way the eye sees color, fluorescent lamps can be designed to create very good color rendition. (Image courtesy of General Electric Company)



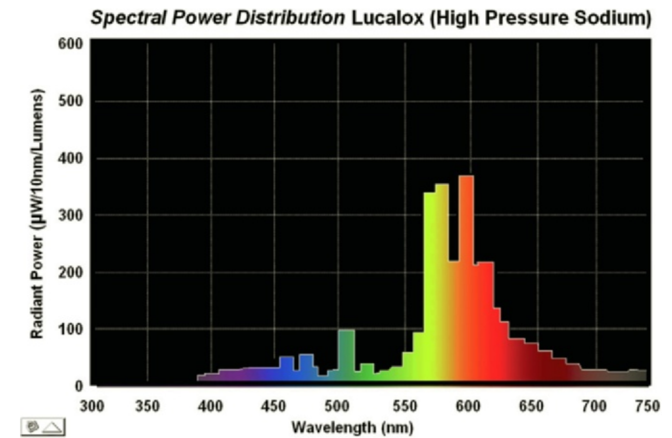
Colorplate 11 This compact fluorescent was designed to create a warm white light (note the large amount of red light) to better replace the very inefficient incandescent lamp. (Image courtesy of General Electric Company)



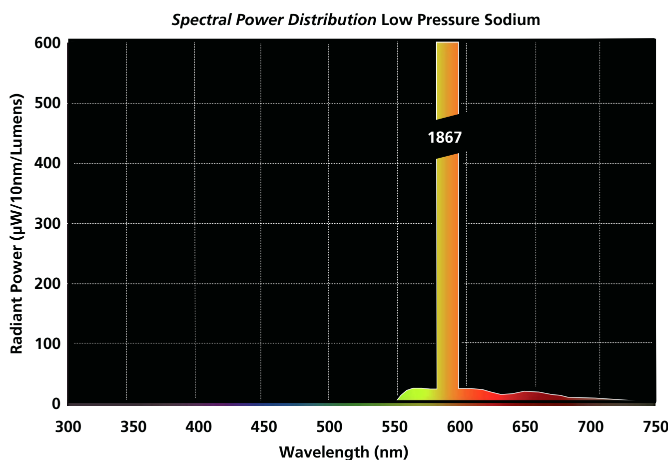
Colorplate 12 Metal halide lamps produce good color rendition at high efficacy in a compact light source. (Image courtesy of General Electric Company)



Colorplate 13 The ceramic metal halide lamp has very good color rendition, and it is more efficient than the halogen lamp it replaces. (Image courtesy of General Electric Company)



Colorplate 14 High pressure sodium lamps have poor color rendition, because most of the light output is in the yellow/orange part of the spectrum. (Image courtesy of General Electric Company)



Colorplate 15 Low pressure sodium lamps are appropriate only where color recognition is not important. They are monochromatic, because almost all light is emitted in the yellow part of the spectrum. (Image courtesy of General Electric Company)



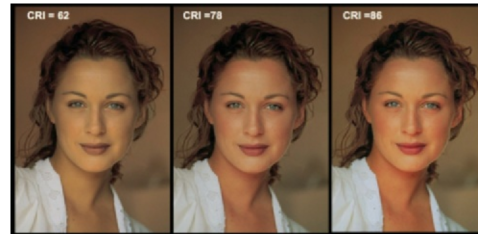
Colorplate 16 This photograph of the main lobby in the Menil Collection in Houston, Texas, clearly demonstrates how much cooler north lighting is than sunlight. The skylight over the lobby is partially shaded by the two-story portion of the museum on the left. The shaded section of the skylight is, therefore, only illuminated by the blue sky. The other portion at the far right is illuminated by both the blue sky and the warm sunlight. Also note the reddish white light produced by incandescent lamps in the side corridor.



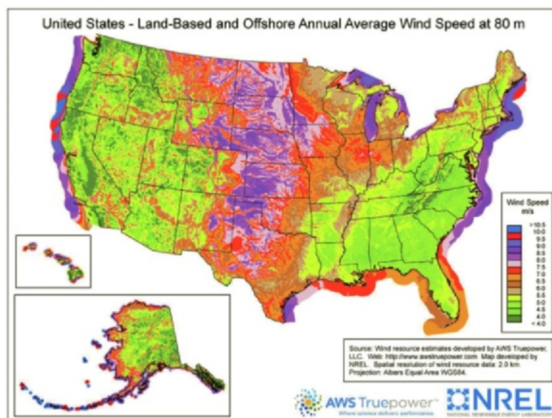
Colorplate 17 Color can be used to create rich and humane architecture. The colorful banners in this library also act as baffles to diffuse daylight and to prevent glare from the skylights. (Photo courtesy Lisa Heschong, Heschong Mahone Group, Inc., 2002)



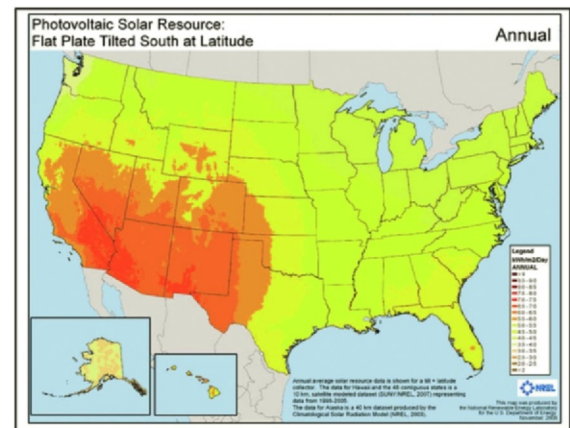
Colorplate 18 White light sources vary in their color temperature, measured in Kelvin. A low number like 2700K is a much warmer light source than a cool color like a 6500K light source. A cool light source is bluish in color, while a warm light source is reddish in color. (Image courtesy of General Electric Company)



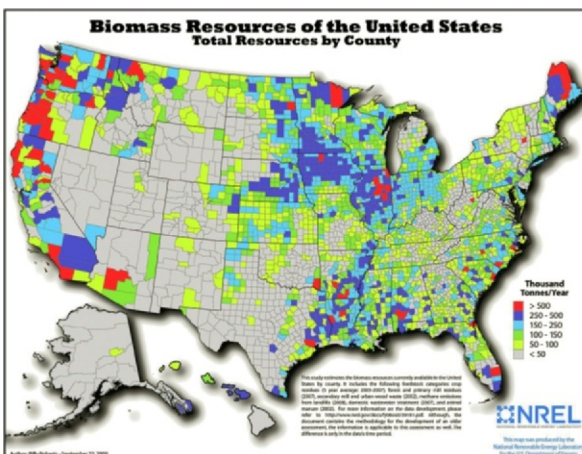
Colorplate 19 The color-rendering quality of a white light source can also be described by the Color Rendering Index (CRI) from 1 (worst) to 100 (best). The higher the CRI, the truer the color. The illustration shows how poorly skin color appears with a CRI of 62 as compared to a CRI of 86. (Image courtesy of General Electric Company)



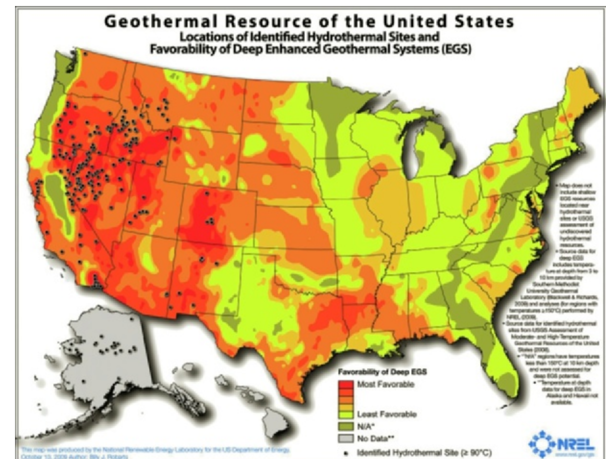
Colorplate 20 Except for special local cases, wind electricity will be mainly produced by large wind turbines located in high-wind areas in the Great Plains, the Great Lakes, and coastal waters.



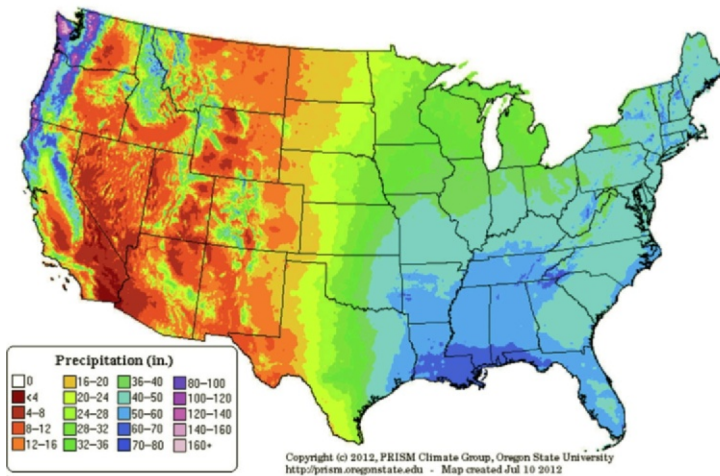
Colorplate 21 There is sufficient solar energy access for photovoltaics (PV) even in the least favorable parts of the United States. For example, in one of the least favorable areas, Portland, Oregon, the 50,000 ft^2 (4500 m^2) office building called the Bullitt Center produces all of its electricity from PV.



Colorplate 22 Fortunately, biomass is most available where solar, wind, and geothermal are least available.



Colorplate 23 High-temperature geothermal resources for generating electricity are mostly located in the western part of the United States. However, medium-high temperatures for generating hot water to heat buildings is much more widely available.



Colorplate 24 Note the close relationships between biomass resources and average annual precipitation.



Colorplate 25 What is the form of this building? It is a shoe box with a very clever and sophisticated mural.

USDA Plant Hardiness Zone Map

Colorplate 26 This plant hardiness map is based on the average low temperatures found at each location. Since temperature is a major factor in determining a climate, this map can help in climatic building design. (This and related maps can be found at http://planthardiness.ars.usda.gov/PHZMWeb/Images/northamerica.jpg.)



Colorplate 27 Vegetated walls can be more valuable than vegetated (green) roofs. High-rise buildings usually have much larger wall than roof areas. East and west walls, which should have few if any windows, can be covered with vegetation such as this climbing vine changing color in autumn.



Colorplate 28 Awnings not only provide shade when needed but also add color and texture to a building. The dynamic awnings in this Chicago restaurant also allow solar access, which is desirable much of the year.



Colorplate 29 In Bermuda, all buildings by law must have a white roof. As a result, the buildings are significantly cooler. (Image courtesy Bermuda Department of Tourism)



Colorplate 30 This apartment building in Rome, Italy, has a dynamic facade of both movable awnings and deciduous plants, which provide shade only when it is needed and wanted. The plants also serve the human need of biophilia.



Colorplate 31 When the author recommends white for a sloped roof, the almost universal response is that white roofs are ugly. The author then whips out a photo of this building and asks, "Is this building ugly because of its white roof?"



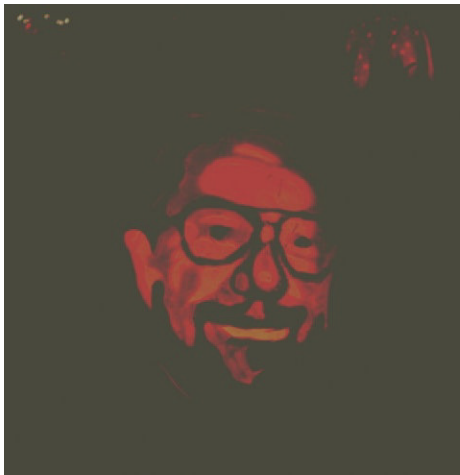
Colorplate 32 The National Library of Singapore, designed by T. R. Hamzah and Ken Yeang, uses white walls, overhangs, and light shelves to minimize heat gain to both the building and the city.



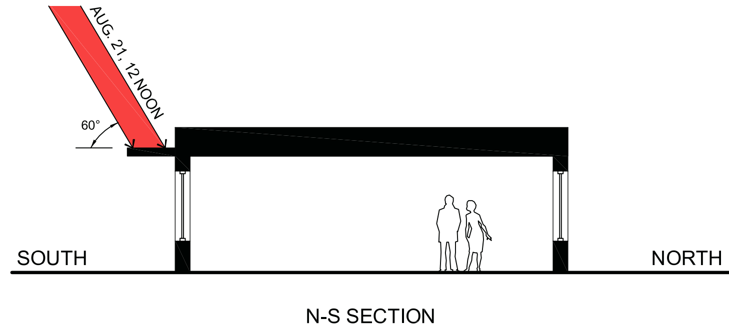
Colorplate 33 Increasingly, people are responding to the fact that the heat gain through a white roof is half of that through a black roof (as stated in the *ASHRAE Handbook of Fundamentals*). Remember, white is the greenest color.

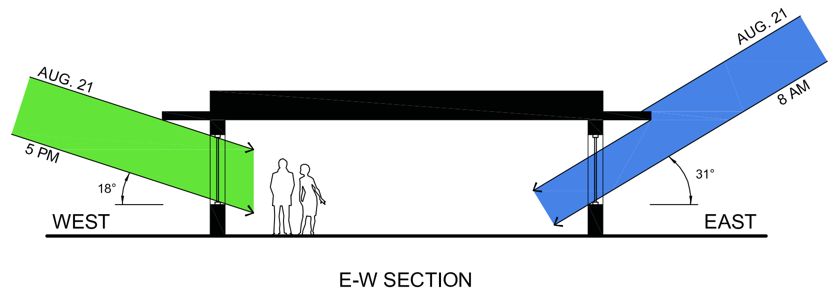


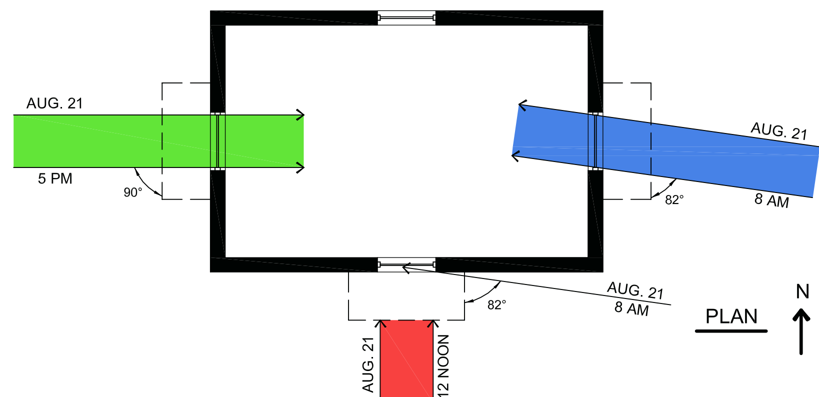
Colorplate 34 What is the function of this building? This elementary school in Bangkok, Thailand, could be an example not only for school buildings but for most other buildings as well.



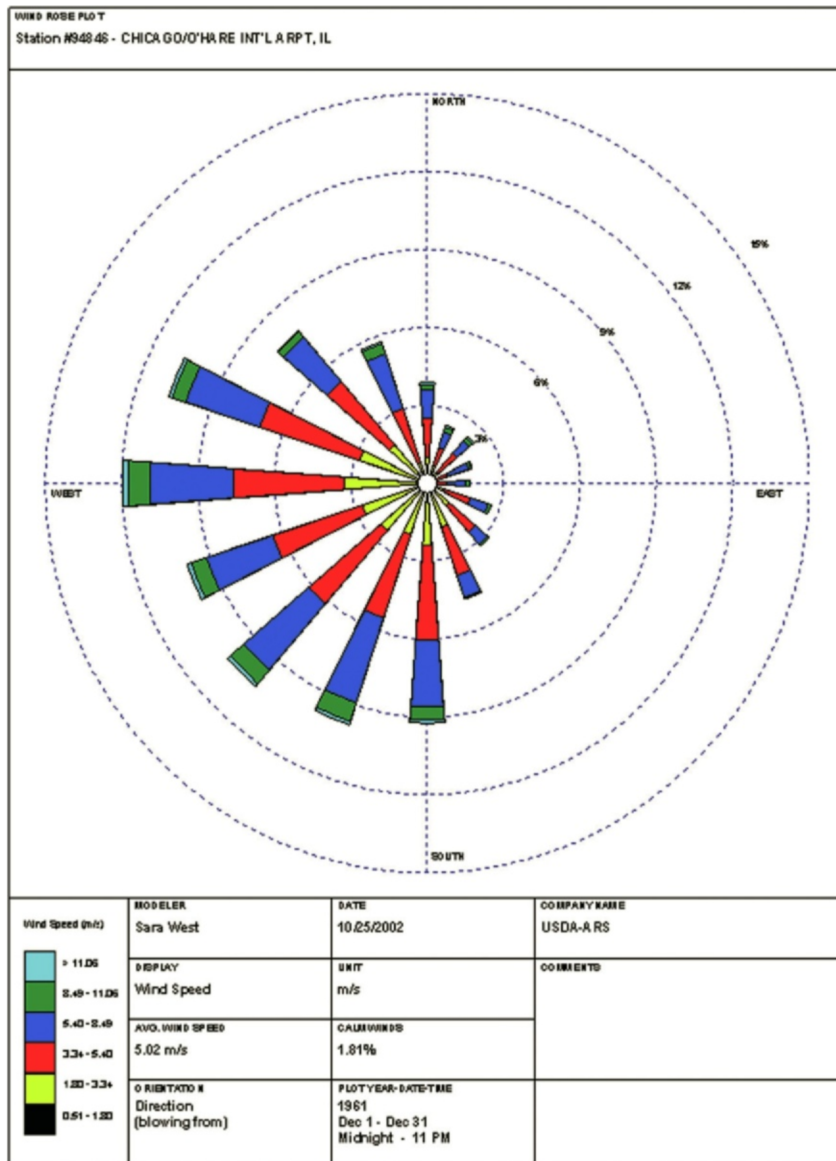
Colorplate 35 Every year, the students at the Architecture School at Auburn University have a pumpkin carving competition. One student, whose name is unfortunately lost, carved an incredible likeness of the author out of a pumpkin. I hope the student who made this carving will see his or her work published here.



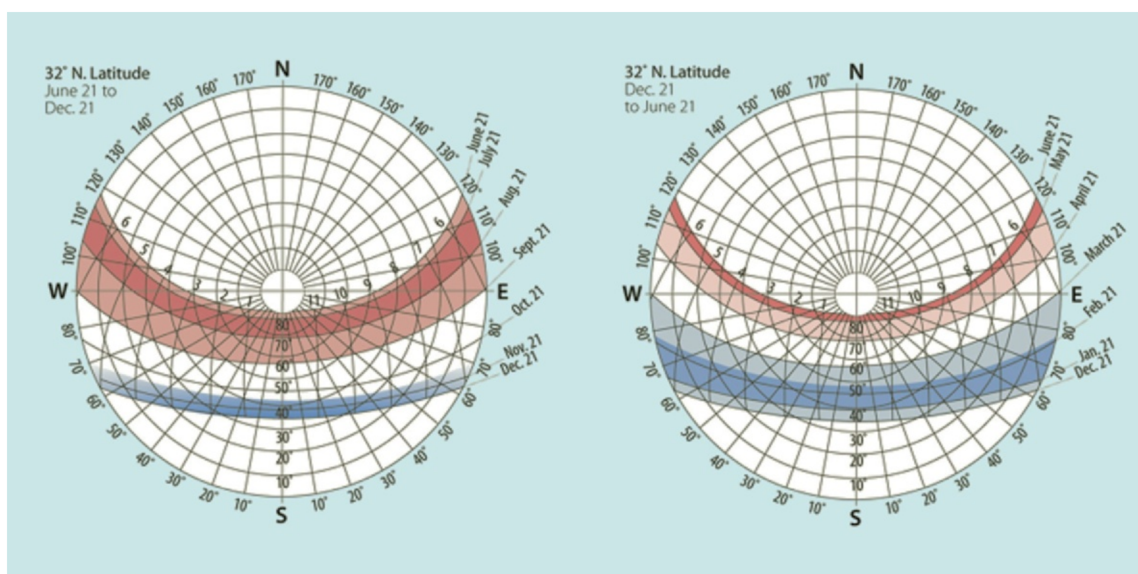




Colorplate 36 In designing, presenting, or teaching solar-responsive architecture, plans and sectors should show sunbeams at critical times of the day and year. At least two sets of drawings are needed: one to show the summer sunbeams (shown) and another to show winter sunbeams (not shown). The usual practice of showing the sunbeams for June and December 21 is misleading. The critical sunbeams are those at the end of the overheated and underheated periods.



Colorplate 37 This wind rose shows the direction and frequency of various wind speeds in Chicago in November. It shows that the wind comes from the south about 9 percent of the time. It also shows that the wind speed is 5.40–8.49 m/s (12–19 mph) a little less than 3 percent of the time (blue). To change wind speed from m/s to mph, multiply by 2.237. Wind roses for most U.S. cities can be found at www.wcc.nrcs .usda.gov/climate/windrose.html.



Colorplate 38 Although sun angles are symmetric about December 21 and June 21, the thermal year is not. The left sun-path diagram is for the six months from June 21 to December 21, and the diagram on the right is for the six months from December 21 to June 21. Note that sun paths are the same because of the annual symmetry. However, the temperatures are not symmetrical. The shades of blue reflect how cold it is, while the shades of red reflect how hot it is. Fixed shading devices perform poorly in part because they respond to the solar year and not the thermal year.

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